World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:13, No:2, 2019

Conventional and Hybrid Network Energy Systems Optimization for Canadian Community

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***Abstract*—**Local generated and distributed system for thermal and electrical energy is sighted in the near future to reduce transmission losses instead of the centralized system. Distributed Energy Resources (DER) is designed at different sizes (small and medium) and it is incorporated in energy distribution between the hubs. The energy generated from each technology at each hub should meet the local energy demands. Economic and environmental enhancement can be achieved when there are interaction and energy exchange between the hubs. Network energy system and CO_2 optimization between different six hubs presented Canadian community level are investigated in this study. Three different scenarios of technology systems are studied to meet both thermal and electrical demand loads for the six hubs. The conventional system is used as the first technology system and a reference case study. The conventional system includes boiler to provide the thermal energy, but the electrical energy is imported from the utility grid. The second technology system includes combined heat and power (CHP) system to meet the thermal demand loads and part of the electrical demand load. The third scenario has integration systems of CHP and Organic Rankine Cycle (ORC) where the thermal waste energy from the CHP system is used by ORC to generate electricity. General Algebraic Modeling System (GAMS) is used to model DER system optimization based on energy economics and CO_2 emission analyses. The results are compared with the conventional energy system. The results show that scenarios 2 and 3 provide an annual total cost saving of 21.3% and 32.3 %, respectively compared to the conventional system (scenario 1). Additionally, Scenario 3 (CHP & ORC systems) provides 32.5% saving in CO_2 emission compared to conventional system subsequent case 2 (CHP system) with a value of 9.3%.

***Keywords*—**Distributed energy resources, network energy system, optimization, microgeneration system.

I. Introduction

THE DER system has gained inclusive attention to build on the vision that future electrical and thermal power systems will be generated and distributed locally and will not be a centralized system as they are today. The localized network of the DER system will be matching the local energy demands. The DER system can be a small or medium size and it is sited near consumers, within energy distribution systems. In addition, the DER system can include storage technology for electrical and thermal energy. The DER system has advantages compared to the centralized system such as it includes local waste energy recovery to generate additional usable energy and increases the overall system efficiency by reducing the primary energy consumption. The DER system reduces the transmission and distribution losses as the generated energy is close to the consumer. Also, the DER system increases the reliability of energy supply to the customers. In addition, it allows using the local renewable energy resources by adding more flexibility and control of energy provided to the consumers. The local energy generation can meet any variation in the heating and electrical demand loads if the local systems are designed properly. Recently, there is more attention from the global community to generate energy from renewable energy resources (e.g. solar, wind, geothermal, hydro, biomass) and from locally generated energy (e.g. CHP system) to reduce carbon dioxide emissions. During the last two decades, there was significant developing in the DER systems. The solar system includes both photovoltaic thermal (PVT) and photovoltaic (PV) energy systems.

Energy system optimization for residential and commercial building applications should consider heating, cooling, and electrical energies, economic and environmental impact. The energy system optimizations have many variables and constraints that make the problem more difficult to be solved. Therefore, many researchers used different programming to solve the optimization problem such as; linear programming [1], [2], mixed integer linear programming [3]-[8], mixed integer nonlinear programming [9]-[13] with reducing the number of constraints and variables and break down the optimization problem into two parts [14]. The optimization problem becomes more complicated for the multi-objective optimization problems.

Ashouri et al. [3] applied mixed integer linear programming by developing a framework for selecting, sizing and controlling the building energy systems for a specific case of the energy hub model. Maréchal and Kalitventzeff [4] applied mixed integer linear programming technique to select the utility system with combined the modeling and practice systems. Fazlollahi and Maréchal [9] proposed an alternative approach to combine mixed integer nonlinear programming with evolutionary approaches for applying the multi-objective optimization. Weber et al. [14] applied a structuring process to divide the optimization problem of district energy systems into nonlinear and mixed integer.

Ren and Gao [15], Mehleri et al. [16], [17], and Omu et al. [18] investigated DER system optimization using mixed integer linear programming (MILP). Yang et al. [19] used GAMS software to model DER system optimization. They concluded that high-energy technology efficiency had a significant effect on economic efficiency and CO_2 reduction compared to fixed efficiency. Omu et al. [18] used IBM ILOG CPLEX model to solve their MILP model. The new

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technology system can lead to a reduction in annual CO_2 emission with more efficient use of primary energy if the DER system is optimally designed [18]. Scala et al. [20] modeled optimal energy flow management in multicarrier energy networks with including interconnected and distributed energy hubs. Their model was nonlinear with multi-objective optimizations study. Parisio et al. [21] presented a robust optimization approach to energy hub management using mixed linear programming model. Brahman et al. [22] studied optimal electrical and thermal energy management of a single residential energy hub by integrating energy production, conversion, and storage technologies. Ren et al. [23] investigated economic optimization and sensitivity analysis of the PV system for residential building applications.

The most literature focus on district heating, cooling and electrical systems optimization and management of energy conversion technologies and their operational strategies [24]-[29]. Three hubs with two technologies are investigated by [30] for optimum economic and emission. However, there are many factors influence on optimum energy planning design such as, local emission regulation, the capital cost, available renewable energy resources, fuel and electrical costs, subsidy for renewable energy, local air quality, building applications and outside weather conditions.

In the present study, an optimization study based on energy economic and emission analyses will be investigated for optimum energy distribution between six different buildings presented Canadian community level under Toronto, Canada weather conditions using three different technology system scenarios. GAMS is used to model DER system optimization.

II. Problem Description

In the present study, six hubs are modeled to present different building applications for the Canadian community. Each hub includes a different technology system to provide electrical or/and thermal energies to meet the demand loads under Toronto weather conditions. Both thermal and electrical energies can be transferred between the hubs as shown in Fig. 1. In addition, the electrical energy can be imported or exported from or to the grid depending on electrical energy generated by different technologies and electrical demand loads required for each hub.

The distributed energy network optimization between the hubs is investigated in this study to identify the optimum local energy generation and the type of technologies need to be installed at each hub. The current study is based on multi-objective optimization to minimize economic cost and environmental emissions. Mixed integer nonlinear programming code is built and developed in the present study using GAMS programming platform to solve a complex nonlinear systems optimization problem.

Several input parameters are used in the mathematical model such as thermal and electrical demand loads for each hub at every time interval, the weather conditions (e.g. outside temperature, solar radiation, wind speed, etc.), gas and electricity tariffs, gas emission tax and financial data.

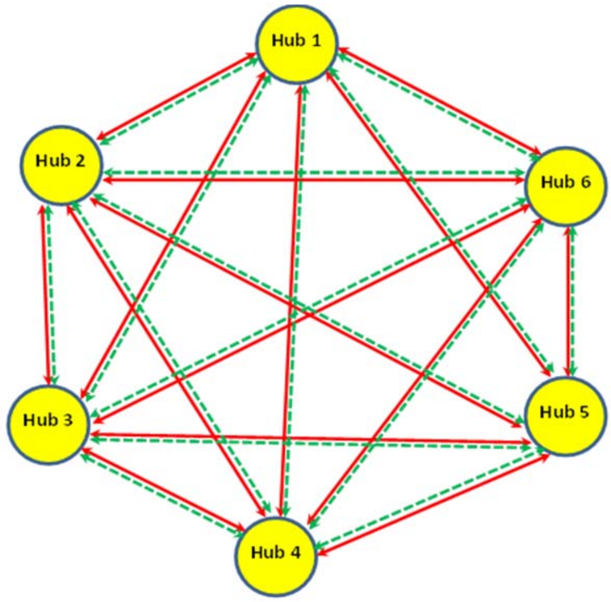


Fig. 1 Energy transfer between hubs and grids (red lines are for thermal and green dot lines are for electrical)

Three different scenarios are investigated in this study and are reported as following:

1. A conventional system where boiler provides thermal heating energy and chiller provides thermal cooling energy whereas the electrical energy is imported from the grid to meet the electrical demand loads.
2. CHP system provides the thermal heating and part of the electrical energy demand loads and the rest of the electrical energy demands are imported from the grid, while the chiller provides the thermal cooling demand loads. Any excess electrical energy is exported back to the grids.
3. Integrated CHP systems with centralizing ORC system to convert the excess thermal energy from the CHP system to electrical energy. Chiller is used to provide the thermal cooling demand loads. The excess electrical energy from the system is exported to the grid and imported when it is needed.

Fig. 2 illustrates schematic energy flow between different technologies, grids and building loads for scenario 3 (CHP and ORC). A single ORC system is installed between the hubs to receive the waste heat from the different technology systems after meeting all thermal demand loads to produce electrical energy. Moreover, a single chiller system is installed at each hub to meet the cooling load. Fig. 2 presents also the input, output energy flows of each hub at every time interval, and the energy flow describes sites of energy generation/consumption for each hub.

III. Optimization Model

The optimization problem is formulated as an advance optimization model since each hub has a unique option to install different technology systems with different capacity sizes. In addition, each hub is connected with heating/cooling pipelines and electrical connection to share and to integrate the thermal and electric energies among the six hubs.

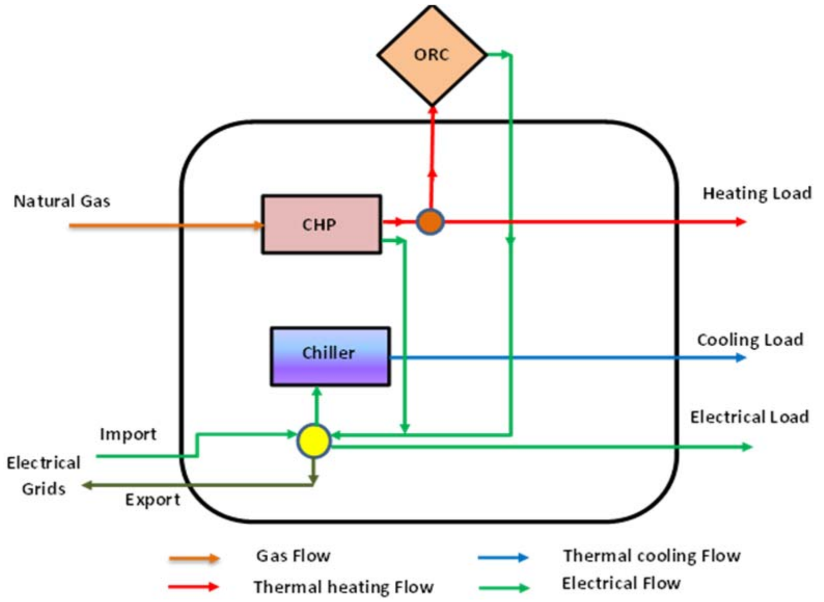


Fig. 2 Schematic of energy modeling and technology details at each hub for case 3 (CHP & ORC system)

A. Modeling Energy Hub

Each hub has multi power flows. There is a converter or multiplication factor to the input power to produce the outlet energy flows as shown in (1) where η_{oi} is the efficiency matrix for the input power flows and F_{oi} is converter unit factor. The element of η_{oi} matrix could be zero which means that there is no conversion exists between the input and output energies. However, if there is a transfer from P_i to L_o, a coupling factor is used for technology efficiency. The coupling factor is equal to the product of the technology efficiencies for more than one energy conversion technology. In order to make each hub model stabilize (matrix multiplication consistent) for the optimization problem, each input energy variable is defined for each unit converter factor.

$$\begin{bmatrix} L_1 \\ \cdot \\ L_o \cdot \\ \cdot \\ L_O \end{bmatrix} = \eta_{oi} * F_{oi} \begin{bmatrix} P_1 \\ \cdot \\ P_i \\ \cdot \\ P_I \end{bmatrix}, \text{Where } \eta_{oi} = \begin{bmatrix} \eta_{11} & \cdot & \eta_{1I} \\ \cdot & \eta_{oi} & \cdot \\ \eta_{O1} & \cdot & \eta_{OI} \end{bmatrix} \quad (1)$$

In addition, the input energy for each technology at all time steps is constrained by the limitation of minimum and maximum capacity as in (2).

$$P_{min} \leq P_i \leq P_{\max} \quad (2)$$

B. Modeling Network Concept

The energy model includes different groups of energy hubs. The hubs are connected by the diversity of network distributions and presented by thermal and electrical demand load profiles. The main input energies for each hub are electricity from the utility grid and natural gas. The output energies (electrical and thermal) from the hub transfer to the demand loads and share between the hubs. The network model is developed for the six hubs. The transferred energy (E_T) from each hub to others is presented in (3). Where E_o is the energy output transfer from the hub to other hubs, N is the total number of hubs. The power energy receives (E_i) by hub from other hubs is presented in (4). EL represents the energy power losses between the hub and other hubs.

$$E_o\,(hub) = \sum_N E_T\,(hub \rightarrow n) \qquad \forall hub \;\&\; hub \notin N \quad (3)$$

$$E_i\,(hub) = \sum_N (E_T\,(n \rightarrow hub) - EL\,(n \rightarrow hub)) \quad \forall hub \;\&\; hub \notin N \quad (4)$$

In the present model, the transferred energy between the hubs is constrained where each hub is not allowed to transfer and receive energy at the same time. Thus, the direction of energy flow is included in the model.

C. Objective Function

The objective function of the optimization model is to minimize the annual cost of the supply energy from different technology systems, purchase/sell electrical energy from/to the grid and environmental emissions cost. The objective function is presented in (5) which includes the capital cost ($C_{capital}$), electrical and fuel costs (C_{fuel} + $C_{electrical}$), operational and maintenance costs (C_{OM}) and emission cost ($C_{emission}$). The revenue costs such as subsidy cost (C_{subs}) for using renewable technology and sell electrical energy cost (C_{sell}) to the grid are subtracted from the annual cost.

$$C_{Obj} = \sum_{Min}(C_{capital} + C_{fuel} + C_{elec} + C_{OM} + C_{emission} - C_{subs} - C_{selling}) \quad (5)$$

D.Constraints

Technology Capacity and Performance

Each technology system provides energy generation constraints at each hub and every time step according to the technology minimum and maximum capacities. The energy generated from each technology system should be between the maximum capacity and minimum allowable part load operation condition at each hub and time step, as shown in (6). This constraint is applied to conventional and CHP technologies.

$$PLR * Max\left(Tech_{Cap.}\right) \leq G_{\ hub,Tech,h,m} \leq Max\left(Tech_{Cap.}\right) \forall hub, Tech, h, m \quad (6)$$

Energy Generation and Demand

This constraint should satisfy the balance between the supply energy from thermal technology systems and the thermal demand loads at each hub every time (h, m) as presented in (7). In addition, the supply thermal energy from all hubs should be balanced with the sum of thermal demand loads at every time step (8).

$$\sum_{Tech} G_{h,m}(heat) \geq Dem_{h,m}(heat) \quad \forall h, m \quad (7)$$

$$\sum_{hub} [\![(\sum_{Tech} G]\!]_{h,m}(heat)\Big) \geq \sum_{hub} Dem_{h,m}(heat) \ \forall h, m \quad (8)$$

Heat recovery from the CHP at every hub and time step is equal to electrical power generation multiply by heat to power ratio (9).

$$G_{hub,CHP,h,m}(heat) = \beta * G_{hub,CHP,h,m}(elec.) \quad \forall hub, CHP, h,\ m \quad (9)$$

A single ORC system with a maximum capacity of 100 kW is receiving the waste heat from the CHP technology system at each hub. The difference between the sum of thermal energy supply by technology systems and summation of the thermal demand loads at every time step enters the ORC system as shown in (10). The output electrical power from the ORC system is equal to the wasted thermal energy from all hubs after meeting the thermal demand loads times ORC system efficiency (11).

$$Q_{ORC,h,m}(heat) = \sum_{hub}(\sum_{Tech} G_{h,m}(heat) - \sum_{hub} Dem_{h,m}(heat)) \quad \forall h, m \quad (10)$$

$$G_{ORC,h,m}(elec.) = \eta_{ORC} * Q_{ORC,h,m}(heat) \quad (11)$$

The electric generated power from technology systems at each hub plus purchase electricity from the grid should balance with the electrical energy demand loads at each hub as in (12). At every time period, the sum of electrical energy generation from all technology systems and imported/exported electrical energy from/to the grid should satisfy the balance of electrical energy demands for all hubs, as shown in (13).

@ each hub;

$$\sum_{Tech} G_{h,m}(elec.) - Dem_{h,m}(elec.) = E(P\ ,T\ or\ S)_{h,m} \quad \forall h, m \quad (12)$$

for all hubs;

$$\sum_{hub}\left(\sum_{Tech} G_{h,m}(elec.) + E(P\ ,\ T\ or\ S)_{h,m}\right) + G_{ORC,h,m}(elec.) = \sum_{hub} Dem\,(elec.) \ \forall h, m \quad (13)$$

Energy Distribution

Each hub cannot distribute energy to other hub/hubs unless it meets its own energy demand loads at each time step as presented in (14). For example, the hub stops to distribute energy to other hubs if the generated energy is less than the energy demand loads at that hub. Moreover, the generated thermal energy from all technologies at each hub is equal to the summation of the thermal demand loads at that hub plus thermal energy transfer from this hub to other hubs at the same time interval as shown in (15). Likeness for at time interval, the electricity generation at each hub is equal to electrical demand loads at that hub plus electricity transfer to other hubs (16).

@ each hub;

$$\text{If } G_{h,m}(heat, elec.) \leq Dem_{h,m}(heat, elec.) \rightarrow \Delta GT_{h,m}(heat, elec.) = 0 \ \forall h, m \quad (14)$$

$$\Delta GT_{h,m}(heat) = \sum_{Tech} G_{h,m}(\ heat) - Dem_{h,m}(heat) \quad \forall h, m \quad (15)$$

$$\Delta GT_{h,m}(elec.) = \sum_{Tech} G_{h,m}(\ elec.) - Dem_{h,m}(elec.) \ \forall h, m \quad (16)$$

Purchase and Selling Energy

Excess or shortage electricity cannot happen at each hub and community level (all hubs) at the same time. The relative magnitude of the energy generation (thermal and electrical) is mainly dependent on energy demand loads and technology used to produce energy. The net excess electricity from the entire hubs is exported back to the grid. The excessed electricity from each hub cannot export to the grid until it satisfies first the electrical energy demands for that hub and for the other hubs. At each time interval, if the sum of generated electricity from different used technologies at all hubs is less than the summation of the electrical demand loads for all hubs, the selling electrical energy to the grid is equal to zero (17). At each time interval, when the generated electricity from all technology at all the hubs is less than the sum of electrical demand loads for all hubs, imported electrical energy from the grid (purchase electricity) is needed to meet the electrical energy difference ($\Delta GT_{h,m}$(elec.)), as shown in (18). The selling electricity to the grid is equal to the difference between the sum of generated electricity at each hub and sum of electrical demands at each hub for each time interval as shown in (19).

$$\text{If } \sum_{hub} G_{h,m}(elec.) \leq \sum_{hub} Dem_{h,m}(elec.) \rightarrow \sum_{hub} \Delta GT_{h,m}(elec.) = ES_{h,m} = 0 \ \forall h, m \quad (17)$$

$$\text{If } \sum_{hub} G_{h,m}(elec.) < \sum_{hub} Dem_{h,m}(elec.) \rightarrow EP_{h,m} =$$

$$-\sum_{hub}\Delta GT_{h,m}(elec.)\ \forall h,m \quad (18)$$

$$\text{If} \sum_{hub} G_{h,m}(elec.) > \sum_{hub} Dem_{h,m}(elec.) \rightarrow ES_{h,m} = \sum_{hub}\Delta GT_{h,m}(elec.)\ \forall h,m \quad (19)$$

E. Cost Calculation

This section presents the estimated cost to calculate the objective optimization function as shown in (5).

Capital Cost

The capital cost is estimated based on the maximum capacity of each technology at each hub times the unit cost multiplied by the pay back cost over the entire lifetime of each technology, as shown in (20). ORC cost is calculated based on the single unit with a capacity of 100 kW for all hubs.

$$C_{Cap.} = \sum_{hub}\sum_{Tech} Max\ (Cap._{Tech}) * C_{Cap.(Tech)} * \frac{R}{1-\frac{1}{(1+R)^{n}}} \quad \forall\, Tech \quad (20)$$

Fuel Cost

The fuel cost is calculated based on fuel consumption by the technology of boiler or/and CHP multiplied by generated energy times the fuel price [31] divided by technology efficiency as presented in (21).

$$C_{fuel} = \sum_{hub}\sum_{Tech}\sum_{m}\sum_{h}\frac{Fp * G_{hub,Tech,m,h}(heat) * ND}{\eta_{Tech}} \quad \forall\, hub, Tech, m, h \quad (21)$$

Electrical Energy Purchase Cost

The electrical cost is presented the electrical energy purchase cost from the grid. It is calculated using (22) based on the electrical imported energy from the grid multiply by electrical price. The calculated electricity price is based on time of use (TOU) price in Toronto, Canada [32].

$$C_{Elec.} = \sum_{hub}\sum_{m}\sum_{h} EP_{hub,m,h} * ND * EP_{price} \quad \forall\, hub, m, h \quad (22)$$

Operation and Maintenance Cost

The operation and maintenance (OM) cost is calculated based on a fraction of the annual capital cost for each technology at each hub, as presented in (23).

$$C_{OM} = \sum_{hub}\sum_{Tech} Max\ (Cap._{Tech}) * C_{Cap.(Tech)} * fr \quad (23)$$

Emission Cost

The emission cost is calculated using (24) based on the tax charge per ton of emission (\$25/ ton of CO_2). The total CO_2 emission from each hub (MP_{CO2}) is produced from natural gas and imported electricity from the grid. On the other hand, generated energy by ORC system reduces the CO_2 emissions with a value of MR_{CO2} (CO_2 mass reduction).

$$C_{emission} = C_{emission\ per\ ton} * \left(\sum_{hub} ND * (MP_{CO2} - MR_{CO2}\right) \quad (24)$$

Subsidies

The new technologies are eligible for an appropriate subsidy to investment incentive in low carbon energy technologies to calculate the revenue stream. The subsidy cost is calculated using (25).

$$C_{Subs.} = \sum_{hub,Tech}(sf_{Tech} * Cost_{cap.}(hub, Tech)) \quad \forall\, hub, Tech \quad (25)$$

Selling Electrical Energy Cost

The cost of selling electrical energy to the grid is calculated based on the excess electrical energy generated by the technologies times electrical selling price which is equal to 75% of the electrical purchase price [32], considering the time of use (TOU) rate, as shown in (26).

$$C_{Selling} = \sum_{hub}\sum_{m}\sum_{h} ES_{hub,m,h} * ND * ES_{price} \quad \forall\, hub, m, h \quad (26)$$

GAMS Model and Assumption

GAMS [33] is a powerful modeling system for mathematical programming and optimization. It is designed for a complex, and large-scale modeling applications. Large sustainable models can be created and adapted quickly to conditions changing. The input data is entered to the mode using "inc" and table formats.

A GAMS model is created to analyze the impact of integrated different technology systems at each hub to provide an efficient thermal and electrical energy network distribution between the energy systems and hubs. The optimization problem becomes complex with nonlinear constraints, thus nonlinear programming is used in this study. The following assumptions are considered to simplify the model problem; electrical sell rate to the grid is 75% of the purchase rate considering time of use (TOU) rate and there is no selling thermal energy to the grid. Average monthly demand load data is used instead of weekly, daily or hourly data to reduce the computational time. The network heat losses between the hubs are neglected. A single ORC unit with a capacity of 100 kW is used to receive the waste heat from all the six hubs.

Case Studies

Six hubs, with conventional and microgeneration systems, were modeled and analyzed for economical energy and environmental emission optimization study under Toronto conditions. As presented in Table I, a combination of six buildings present Canadian community level including; four-story MURB, ten-story MURB, a single office (OF), strip mall (SM), Quick service restaurant (QSR) and primary school (PS). The hubs are mixing of residential and commercial buildings to serve the community. Each building has unique energy profile and peak value. The surface area and technology system capacities of each hub are presented in Table I. Moreover, Table II presents the performance, the characteristics, and the capital cost for the different technology systems used in the present study. The generated thermal and electrical energies are shared between the hubs thus; there is a significant reduction in the system capacity at each hub due to load shift. Therefore, a substantial reduction in the capital cost can be achieved.

TABLE I
HUBS AND TECHNOLOGY SYSTEMS SPECIFICATIONS

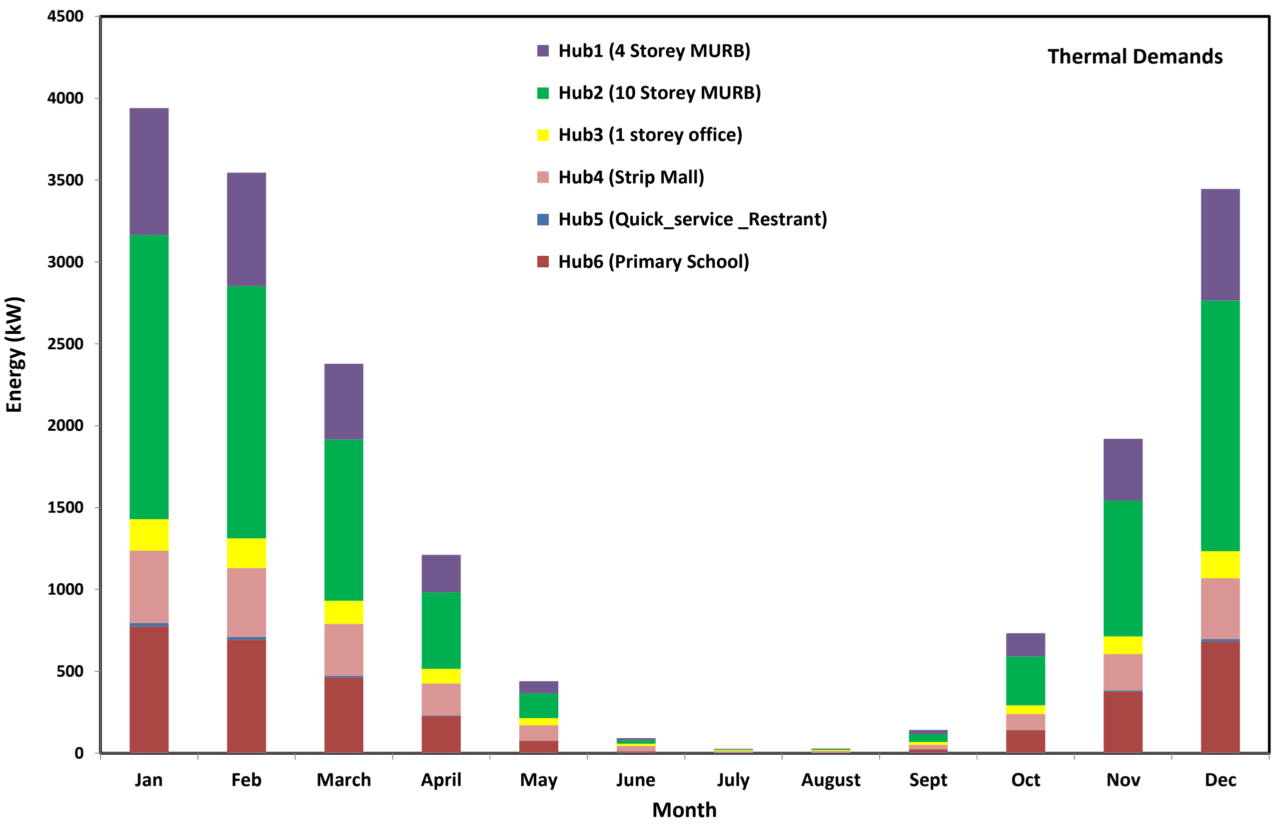
	Hub1	Hub2	Hub3	Hub4	Hub5	Hub6
Area /Technology	1-Story MURB	10-Story MURB	1-Story OF	SM	QSR	PS
Area (m^2)	782.5	782.5	511	2091	232	6871
Boiler (kW)	60	120	20	40	30	70
CHP (kW)	30	60	10	20	15	35
ORC (kW)	100					

TABLE II
SUMMARY OF TECHNOLOGY PERFORMANCE CHARACTERISTICS

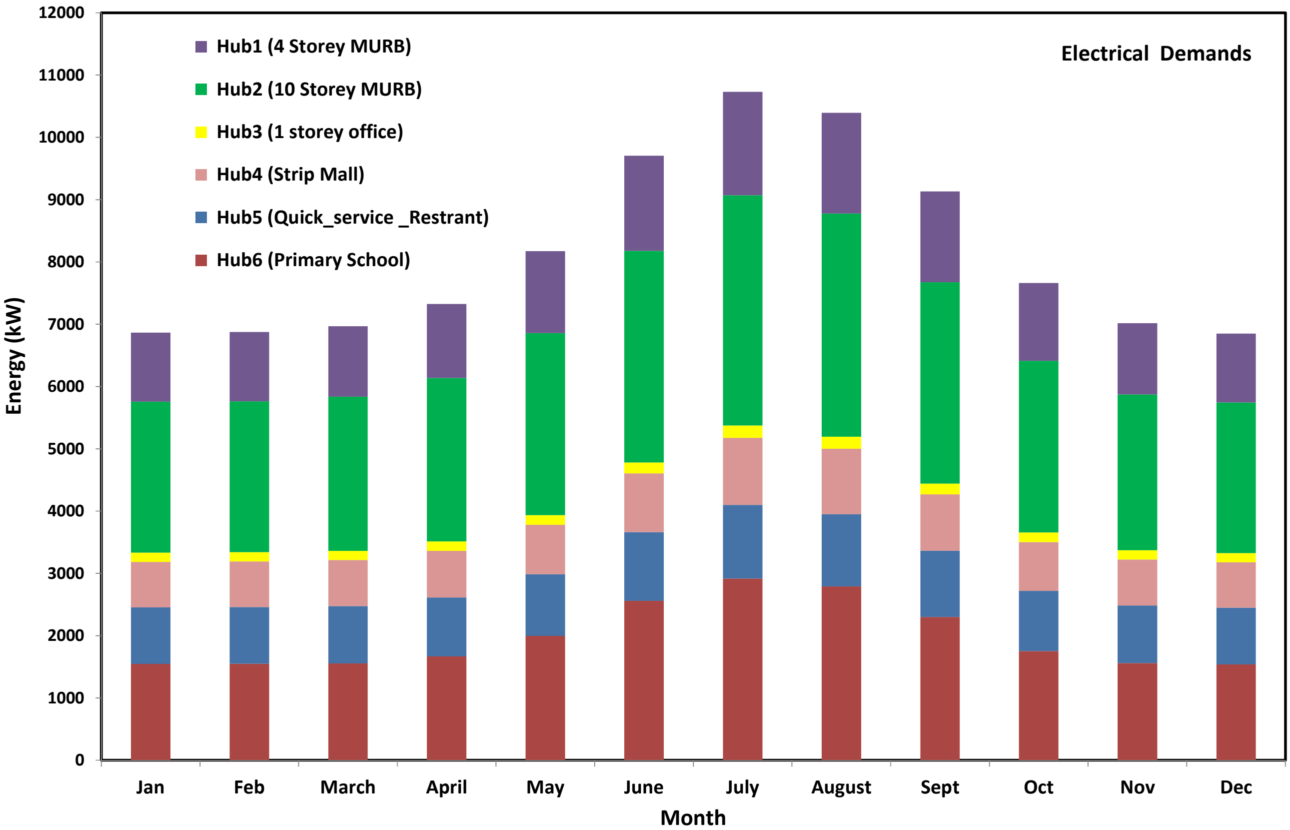
Technology	Capacity (kW)	Efficiency (%)	Lifetime (yr)	Heat to power ratio	Capital cost ($/kW)
Boiler	20	95	30	-	85
	30	95	30	-	85
	40	95	30	-	85
	60	95	30	-	85
	70	95	30	-	85
	120	95	30	-	85
CHP	10	40	15	2	1500
	15	40	15	2	1500
	20	40	15	2	1500
	30	40	15	2	1500
	35	40	15	2	1500
	60	40	15	2	1500
ORC	100	19	25	-	3000

Fig. 3 (a) shows monthly thermal energy demand loads of the six hubs. Hub 2 (10-storey MURB) has the highest heating load during the winter season compared to other buildings. However, Quick service restaurant building (hub 5) has the lowest heating load profile during the winter season because of a high internal heat gain that assists in heating. The thermal demand loads for different buildings in the summer season are related to DHW usages.

Fig. 4 (b) illustrates monthly average electrical energy demand loads of the six different hubs. Hub 2 (10-storey MURB) has the highest electrical energy demand loads over the year compared to other buildings. However, Hub 3 (single story office) has the lowest electrical energy demand loads among other hubs. The electrical load profile increases in the summer period due to a high cooling demand loads.



(a) Thermal



(b) Electrical

Fig. 3 Monthly average thermal and electrical energy demand loads for different buildings

IV. Results and Discussions

A. Thermal Energy

Thermal demand loads including heating and domestic hot water are provided by the boiler in scenario 1. A condensing boiler is used at each hub with different capacity (shown in Table I). The thermal energy can transfer between the hubs. CHP system (Scenario 2) is installed with different capacity at each hub to provide the thermal and electrical energies. Heat to power ratio (β) for the CHP systems is equal to 2. Due to high electrical energy demands for the hubs compared to the thermal demand loads, the CHP system produces higher thermal energy than that required to meet the demand loads. Part of the generation thermal energy by the CHP system is used to provide the thermal demand loads and the rest is wasted heat. Scenario 3 includes a single ORC system with a maximum capacity of 100 kW and it is integrated with CHP systems at the six hubs. The wasted thermal energy (the difference between generated thermal energy from the CHP systems and the thermal demand loads) is utilized by the ORC system to produce electricity. The ORC system efficiency is 19%. The electrical energy generation by the ORC is provided to the electrical demand loads for the six hubs.

Figs. 4 and 5 present the total thermal demand loads for the six hubs and the thermal energy produced by different three studied scenarios during a winter month (January) and a summer month (July), respectively. The results show that the modulating boiler operates to meet different thermal loads (part and full loads). The generated thermal energy in the summer is small compared to that in winter, as it is mainly to meet the DHW thermal loads for the six hubs. Moreover, the CHP system produces thermal energy higher than the thermal demand loads for the six hubs, thus there is excessed thermal energy. Due to high electrical demand loads and less thermal demand loads during the summer, the wasted thermal energy increases for Scenario 2, as shown in Fig. 5. In addition, the Figs. 4 and 5 show the thermal energy breakdown, which is including demand loads, generated thermal energy by CHP and transferred to the ORC system for Scenario 3 during January and July months, respectively. From the results, the thermal energy provided to ORC increases at low thermal demand loads and vice versa. In the summer season, more than 97% of the thermal energy generated by CHP is transferred to the ORC system where the thermal demand loads are only for the DHW.

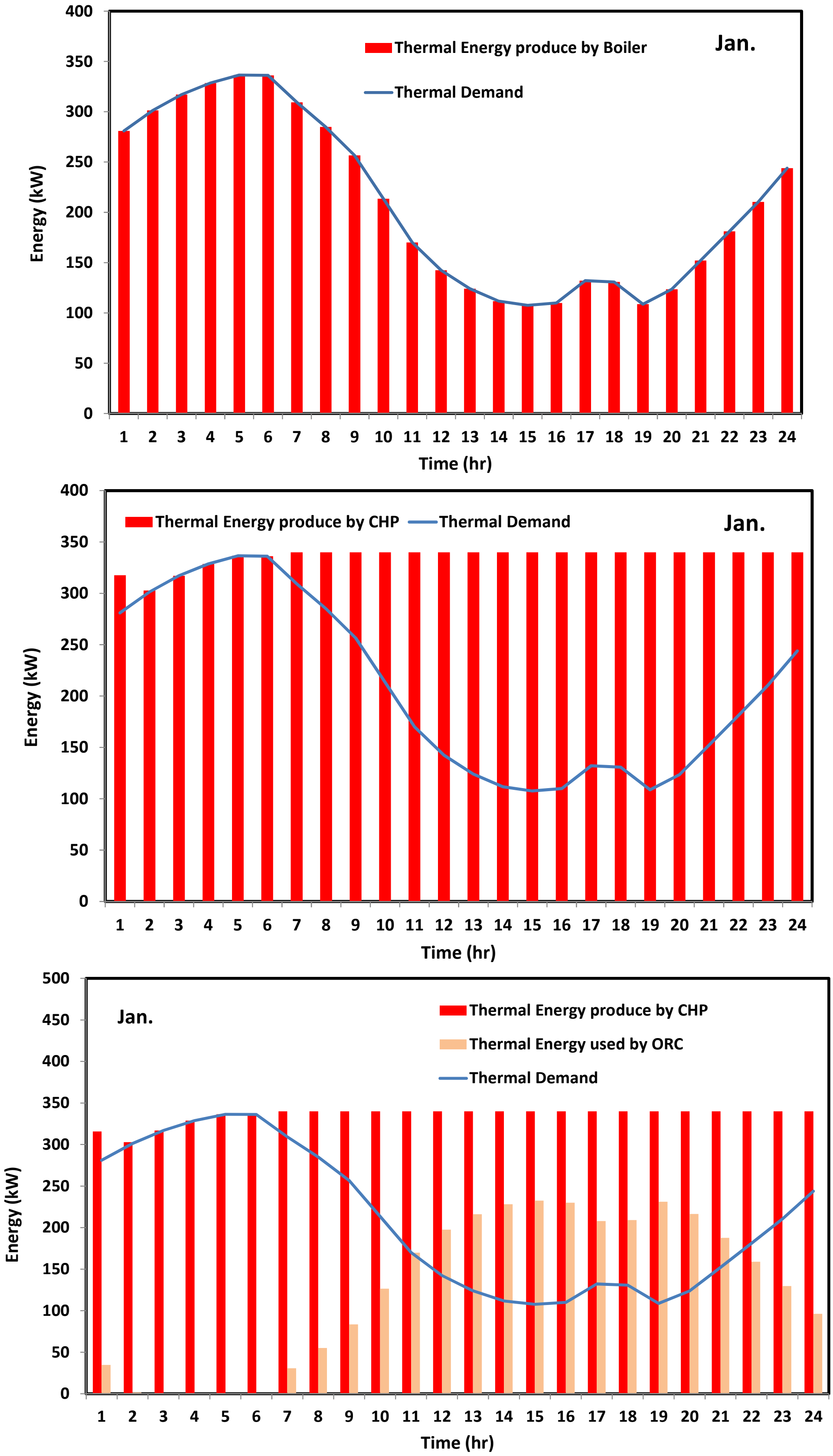


Fig. 4 Thermal energy produced by different technologies and total thermal demand loads (for six hubs) during winter month (January)

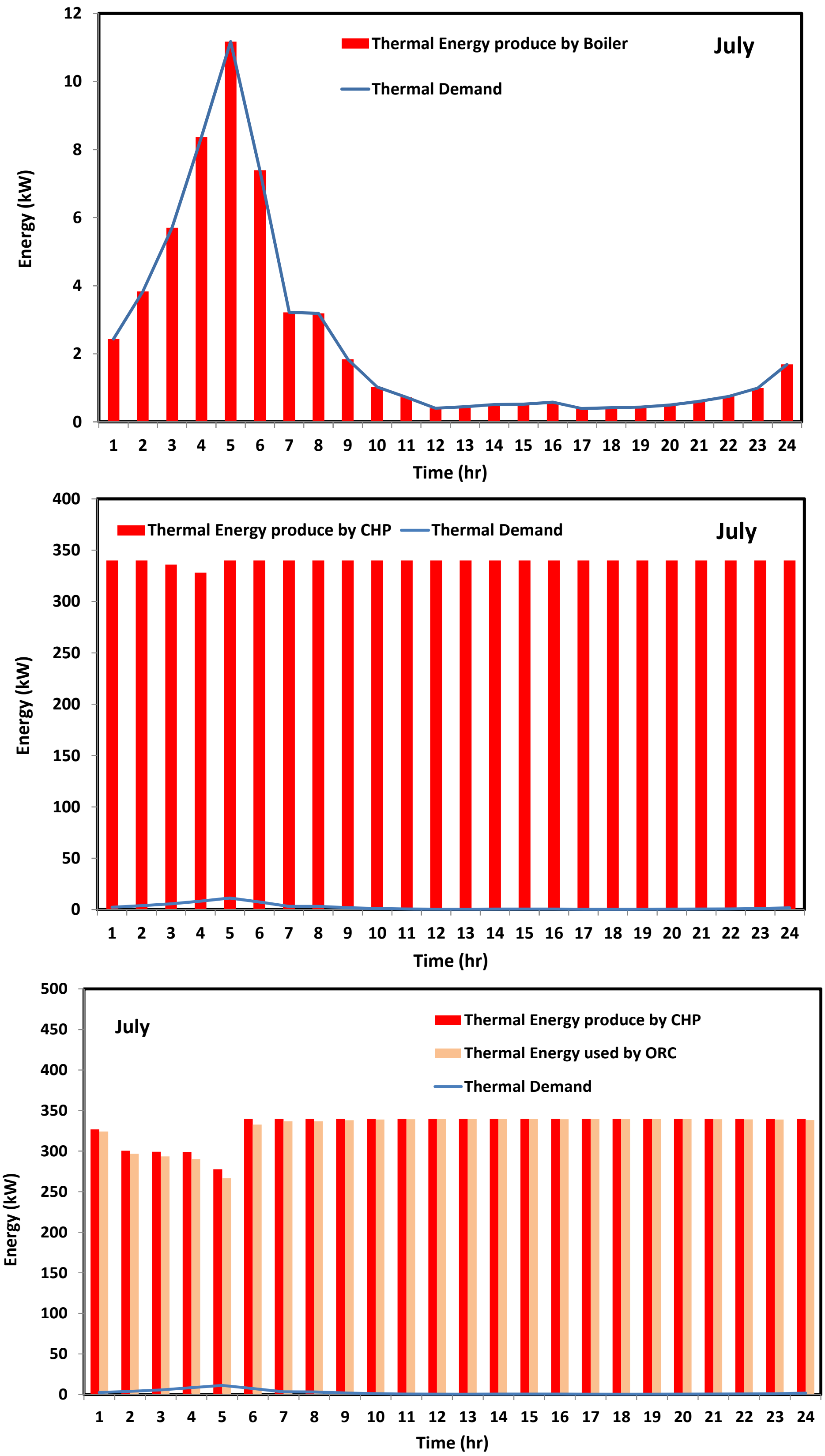


Fig. 5 Thermal energy produced by different technologies and total thermal demand loads (for six hubs) during the summer month (July)

B. Electrical Energy

The electrical demand loads for the six building types are presenting the HVAC and Non-HVAC electrical power consumptions. For case 1 (conventional system), the electrical power is imported from the grids to meet the electrical demand loads for the six hubs as there is no any technology used to generate electrical power. However, for the second scenario, the electrical energy produced by the CHP system is used to meet the electrical demand loads at each hub. The excess electrical energy from each hub in the second scenario can transfer to other hubs, which are not having sufficient generated electricity by their own CHP systems. Afterward, the total generated electricity meets the total demand loads, the net electrical energy; the difference between the generated electricity from all CHP systems and the total electrical demand loads is exported back to the grid. If the generated electricity from CHP systems is not sufficient to meet the total electrical demand loads, the difference between the electrical demand loads and generated electrical energy is imported from the grid. However, in Scenario 3, the waste heat from CHP systems that excessed the thermal demand loads is used by ORC system to generate electric power. The generated electric power from CHP and ORC systems in Scenario 3 is delivered to the electrical demand loads. If the generated electricity from CHP and ORC systems is greater than the electrical demand loads, the difference between the generated and demand electrical energy is exported back to the grid and vice versa.

Figs. 6 and 7 demonstrate the breakdown of average electrical energy for the six hubs under different technologies and the electrical demand load profiles during January and July months, respectively. The highest electrical energy consumption occurs in the summer months where the cooling demand loads are high. The CHP system is able to provide the average electrical demand loads. The electrical power is selling back to the grid when the generated electrical energy is greater than the electrical demand loads, and this occurs after midnight to early morning for Scenarios 2 and 3, as shown in Figs. 6 and 7. If there is no any waste thermal energy, there is no electrical energy produced by ORC system and this can happen early morning during the winter season. Purchasing electricity from the grid is mainly occurred during the daytime in the winter and summer months due to high electrical demand loads in the commercial buildings.

C. Environmental Emission

Fig. 8 (a) presents average CO_2 emission profiles for the three scenarios during the January month. During the winter season, the CO_2 emission is mainly produced from thermal energy generation to meet the heating demand loads in addition to importing electrical energy from the grid. The results show that the conventional system produces the highest amount of CO_2 emissions among other two scenarios. Scenario 3 provides the lowest CO_2 emission during the daytime in the winter from 7:00 until 24:00 where the electrical energy produced by ORC system reduced the CO_2 emissions. Moreover, the CHP and ORC systems (Scenario 3) provide almost constant CO2 emissions during the daytime (from 8:00 to 16:00) in January where the thermal energy output from the CHP system is constant during that time, as shown in Fig. 8 (a). Furthermore, in the early morning, the two scenarios (2 and 3) provide the same CO_2 emissions because the ORC system is not working, as there is no waste heat energy from the CHP system.

On the other hand, the CO_2 emissions increase during the summer season in the daytime due to high electrical demand loads. Fig. 8 (b) demonstrates average CO_2 emission profiles from the three scenarios during July month. From the results, the CO_2 emissions reduce during the night time and increase during the daytime where the cooling demand load is high. Scenario 3 (CHP & ORC) produces the lowest CO_2 emissions compared to Scenarios 1 and 2. There is no significant difference in the CO_2 emissions from the conventional and CHP systems, as shown in Fig. 8 (b).

D. Impact of Technology on Energy Distributions and CO_2 Emission

1. Energy Distributions at Different Hub

Energy at the hub is a flexible interface between the natural gas distribution system and electrical networks [20]. It is an influential model, which can be used to represent the interactions of different technologies for energy conversion and storage. The total annual thermal demand loads and thermal energy generations at different hubs for the three different technology case studies are presented in Fig. 9 (a). The results show that there is thermal energy sharing between the hubs to meet the thermal demand loads using the conventional system. Because of using CHP system technology on the scenarios 2 and 3 and the electrical demand loads is higher than the thermal loads, the systems generate thermal energy higher than the thermal demand load at each hub as shown in Fig. 9 (a). Accordingly, the CHP system produces thermal energy sufficient to meet the thermal demand loads at each hub.

Fig. 9 (b) shows the annual electrical demand loads and electric power generated by the system at each hub for different scenarios. A single unit of ORC system is used in scenario 3 as mentioned previously. The electrical energy produced by ORC system is serving the six hubs. The hub 3 (1-story office) has the lowest electrical demand load compared to other hubs, while the hub 2 (10-story MURB) has the highest electrical demand load. The electrical energy generation at hub 3 (1-story office) is always higher than the electrical demand load for scenarios 2 and 3, thus the excessed electrical energy at hub 3 transfers to other hubs.

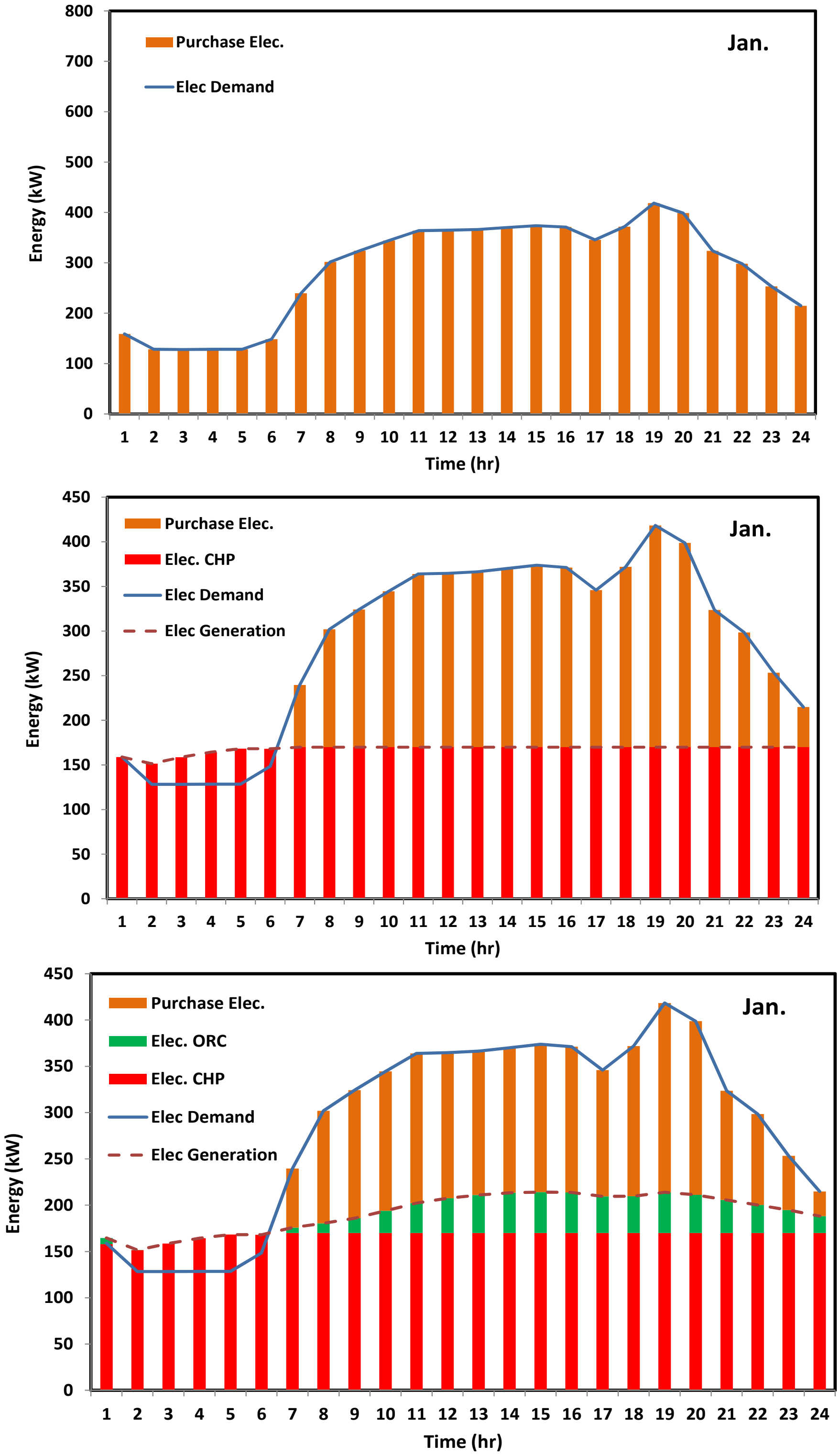


Fig. 6 Electrical energy produced by different technologies, import/ export from/to the grids and total electrical demand loads (for six hubs) during winter month (January)

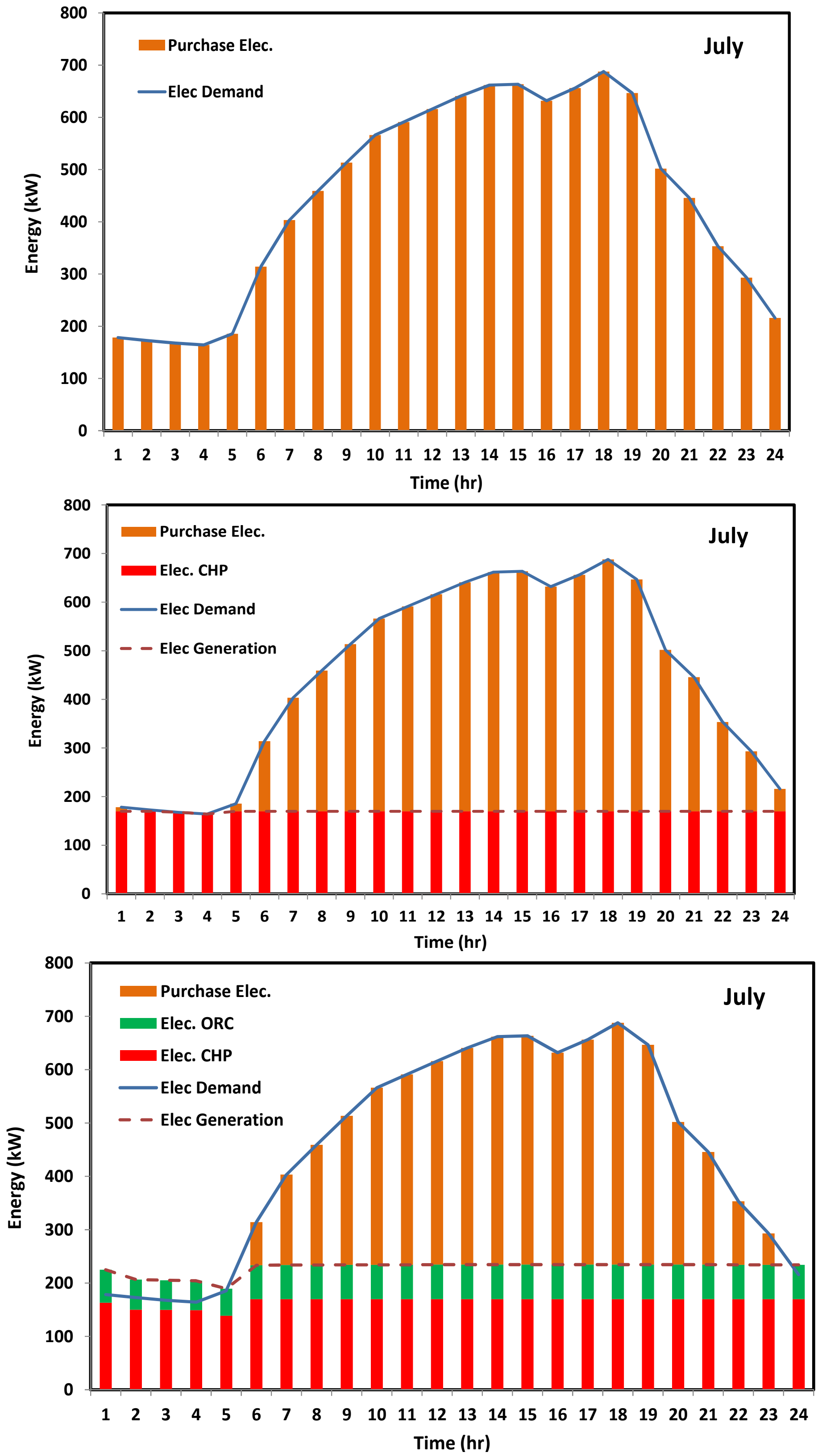
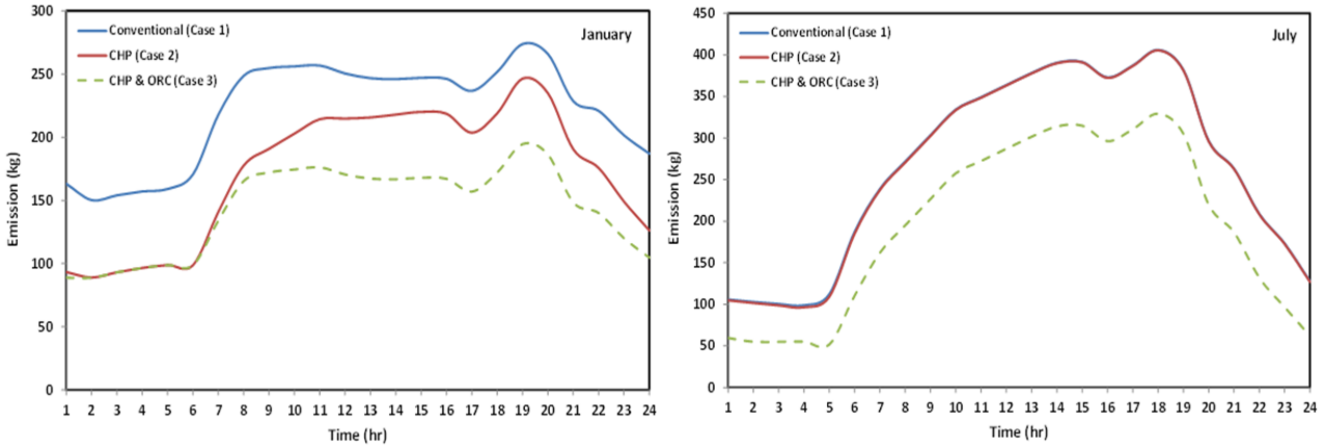
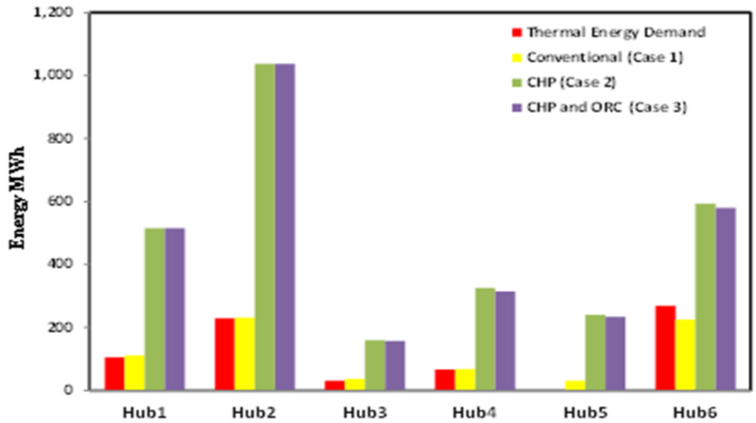


Fig. 7 Electrical energy produced by different technologies, import/ export from/to the grids and total electrical demand loads (for six hubs) during the summer month (July)

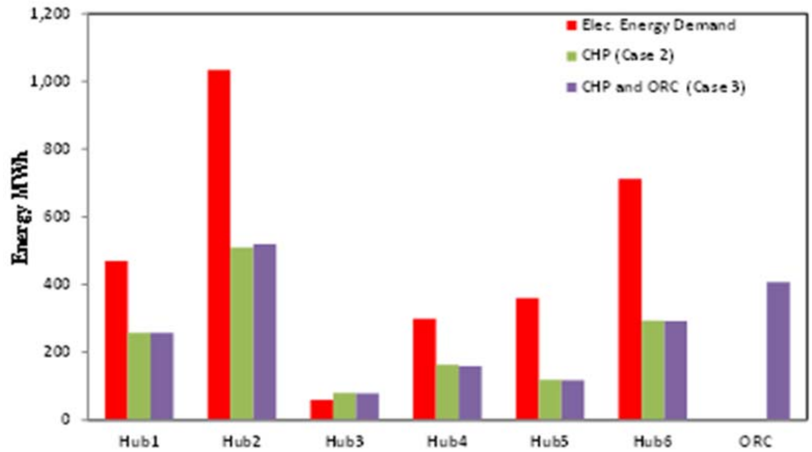


(a) Thermal (b) Electrical

Fig. 8 Monthly average CO_2 emission at different scenarios for months of January and July



(a) Thermal



(b) Electrical

Fig. 9 Thermal and electrical energy distributions at each hub for different scenarios

Fig. 10 illustrates the annual electrical demand loads and electrical energy generated, purchased and sold from/to the grid for different scenarios. The result shows that case 3 (CHP &ORC systems) has the lowest purchased energy from the grid, but the conventional system has the highest purchase electricity from the grid compared to other scenarios. This is due to high electrical energy generation from CHP and ORC systems for Scenario 3, while the entire electrical energy is imported from the grid to meet the demand loads for the conventional system (case1). In addition, scenario 3 has a higher exported or sold electrical energy to the grid compared to Scenario 2.

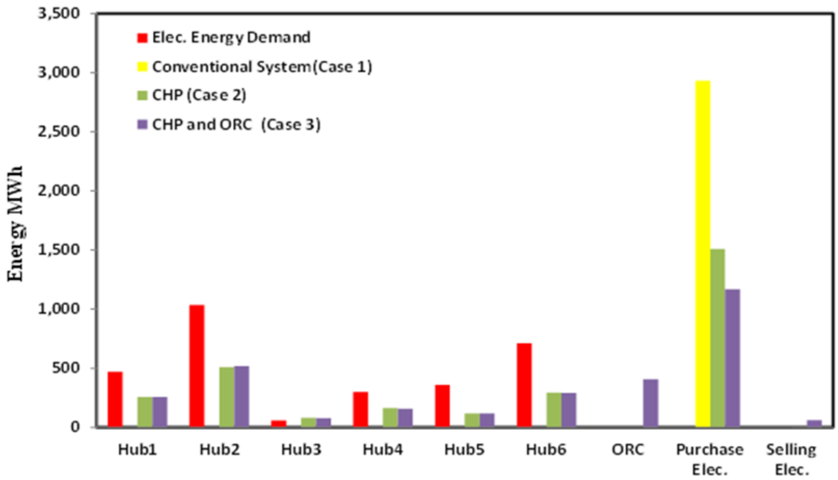


Fig. 40 Electrical energy demanded, generated, purchased and sold for different scenarios

2. Energy Distribution and CO_2 Emission for Different Scenarios

Fig. 11 presents the annual electrical energy distribution at the community level between the demand loads and the electrical energy generated by different technologies, purchasing or selling from/to the grid for different three scenarios. For case 1 (conventional system), 100% of the annual electrical energy demand is purchased from the grid. However, in Scenario 2, the electrical energy purchased from the grid is about 51.5% of the total electrical energy demands and 48.5% provided by the CHP system. In addition, about 0.084% of generated electrical energy is exported back to the grid and demand loads use 99.9%. On the other hand, the purchased electricity from the grid reduces to 39.8% of the total electrical demand loads in Scenario 3. The CHP and ORC systems provide about 60.2% of electrical energy demand load and 3.3% of generated electricity (from both CHP and ORC systems) is selling back to the grid. The CHP and ORC produce 77.8% and 22.2% respectively of the total electrical energy generation as shown scenario 3 in Fig. 11.

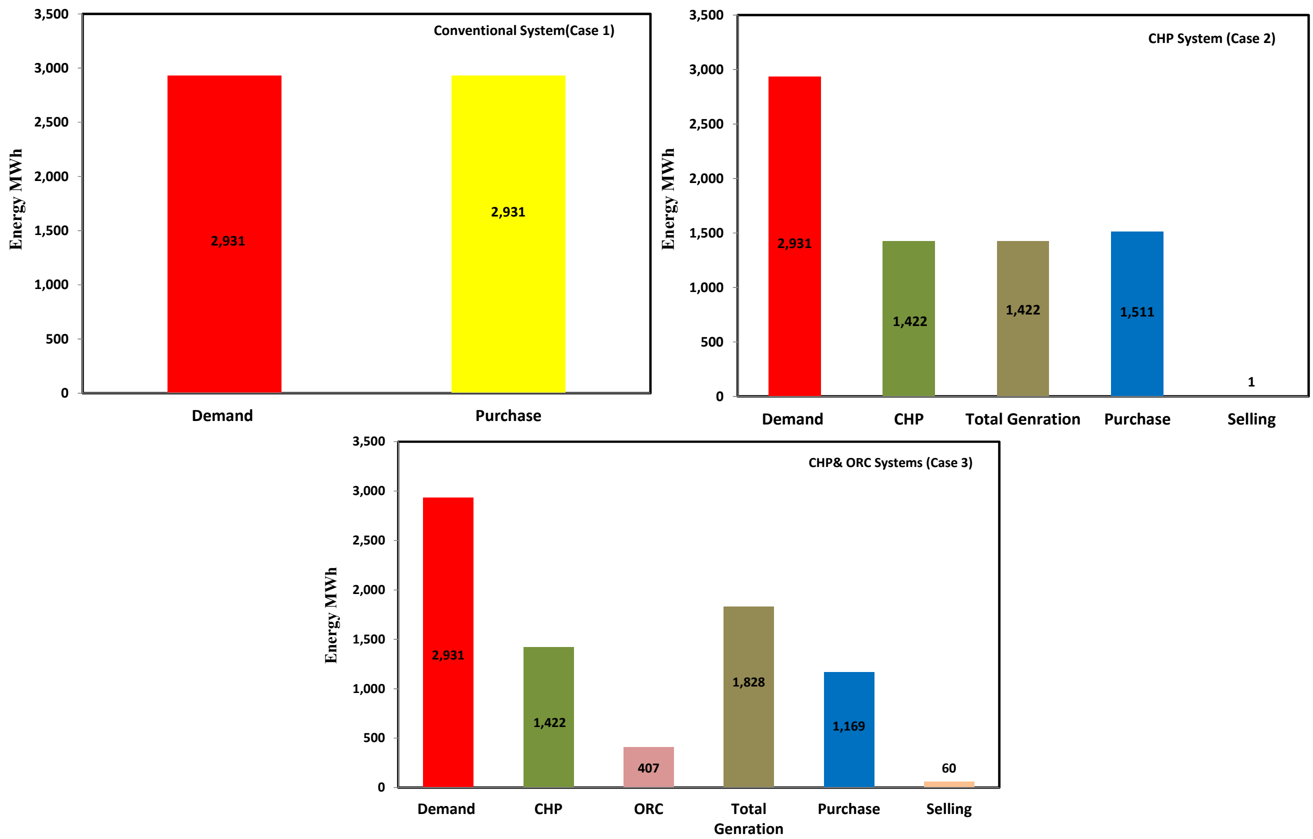


Fig. 51 Electrical energy distributions for different scenarios

Annual CO_2 emissions produced from the different three technologies are presented in Fig. 12. The result shows that the CHP system is able to reduce the CO_2 emission compared to the conventional system. The CO_2 emission reduces significantly by integrated the ORC with the CHP system hence electric power generation is produced from waste heat by the ORC system.

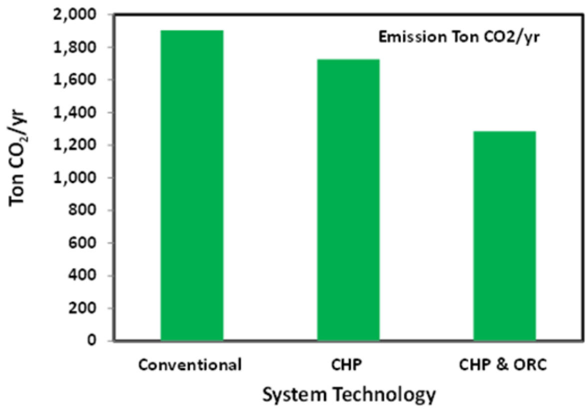


Fig. 62 CO_2 emission from different technologies

E. Cost Analysis Results for Different Scenarios

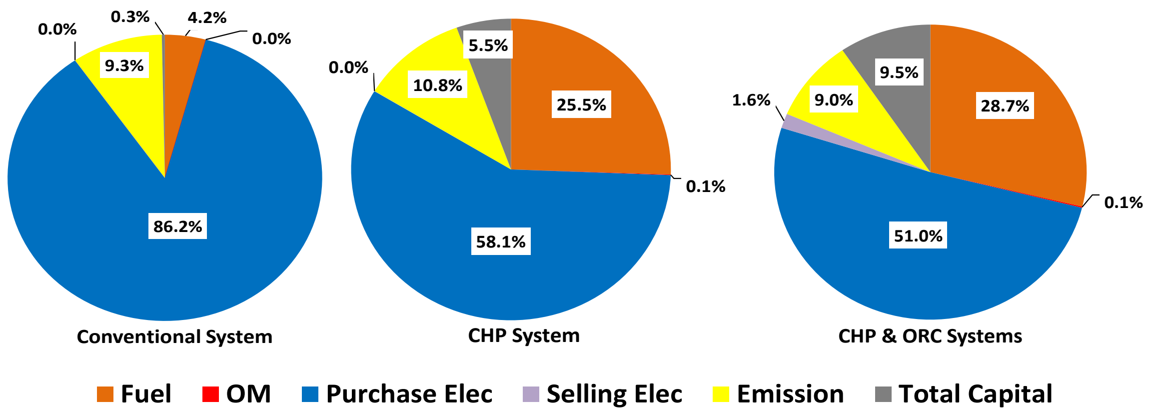
Fig. 13 (a) demonstrates a breakdown of annual cost analysis for different three scenarios to provide electrical, thermal including heating and cooling demand loads. For the case 1 (conventional system), the results indicate that the highest annual cost for purchasing electricity with a value of 86.2%, followed by emissions cost (9.3), fuel cost (4.2%), total capital cost (0.3%), and OM cost (0.004%). For the CHP system (scenario 2), the purchased electricity from the grid has the largest sharing with value of 58.1%, followed by fuel cost (25.5%), emissions cost (10.8%), CHP capital cost (5.5%), OM cost (0.1%) and selling electricity to the grid (0.03%). On the other hand, for scenario 3 (CHP & ORC systems), the purchase electricity cost from the grid presents the highest value of 51% followed by fuel cost with value of 28.74%, the capital cost (9.52%), emissions cost (9%), selling electricity to the grid cost (1.6 %) and OM cost (0.14%).

As a result, the purchasing electrical energy from the grid has a significant impact on the cost of the three scenarios where the electrical demand loads are very high for the commercial building applications. However, the purchasing electrical cost from the grid is reduced using the CHP system (case 2) and reduced more for case 3. The OM cost has the lowest value for the three scenarios.

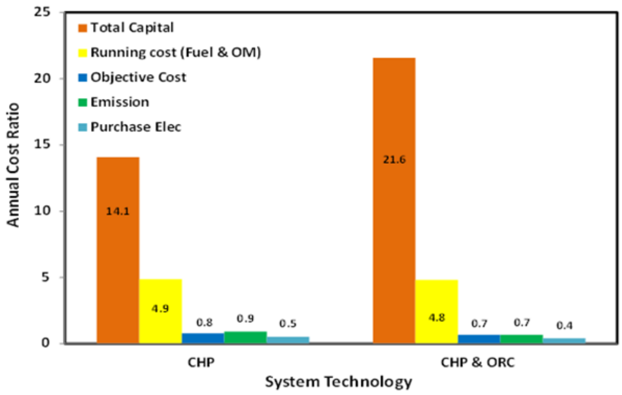
Fig. 13 (b) presents the annual cost ratio of Scenarios 2 and 3 compared to the conventional system (case 1) in term of capital, running (fuel and OM), objective, emission and purchasing electricity costs. The results indicate that the capital cost ratio for Scenarios 2 and 3 is about 14.1 and 21.6, respectively compared to the conventional system (case 1). The difference in running cost ratio (fuel and OM) between cases 2 and 3 is small with a value of 0.1 compared to case 1. The objective cost for cases 2 and 3 is higher than that for a conventional system, and this is mainly due to the high capital cost for cases 2 and 3. However, the cases 2 and 3 achieve a reduction compared to case 1 in the annual cost with a value of 10% and 30%, respectively for the emission cost in addition to 50% and 60% for the purchasing electricity from the grid.

F. Total Cost and Green House Gas (GHG) Emission Saving

Fig. 14 shows annual cost and emission savings for scenarios 2 and 3 with respect to the reference case (conventional system). The results show that the CHP system (scenario 2) provides about 21.3% in annual cost saving compared to case 1, whereas CHP and ORC systems achieve annual cost saving of 32.3% with respect to the conventional system. On the other hand, case 3 (CHP&ORC system) provides 32.5% emission saving compared to the conventional system and 9.3% for case 2 (CHP system), as shown in Fig. 14.



(a)



(b)

Fig. 73 Cost analysis for different scenarios

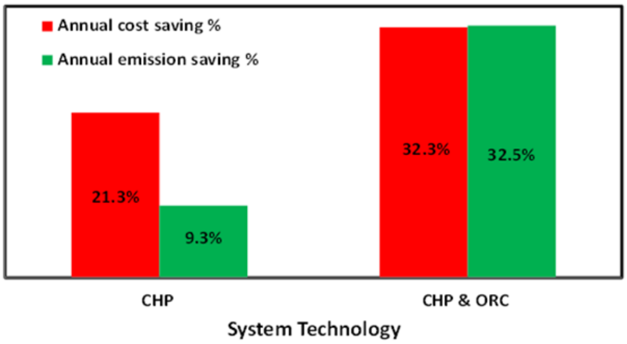


Fig. 84 Overall cost and CO_2 emission saving compared to the conventional system

V. Conclusions

In this study, thermal and electrical demand loads for different six building applications (presenting Canadian community) under Toronto weather condition are used in optimization study using three different technology scenarios; conventional, CHP and CHP&ORC systems. The optimization study is carried out the annual analysis of capital, running, CO_2 emission, and annual total costs. In addition, the annual total cost and CO_2 emission savings are presented compared to the conventional scenario.

The following are the conclusions derived from the optimization analysis for different systems serving six hubs:

- Mixing hubs to include residential and commercial buildings is able to reduce the selected equipment capacity as the thermal and electrical demand loads are shifted between different building applications.
- For the second scenario (CHP), the electrical energy purchased from the grid is about 51.5% of the total electrical energy demands and 48.5% provided by CHP. About 0.1% of the generated electrical energy is selling back to the grid.
- Integrated ORC and CHP systems reduce the purchased electricity from the grid to 39.8% of the total electrical demand loads and 60.2% provided by CHP & ORC systems. About 3.3% of generated electricity is selling back to the grid.
- For scenario 3, the CHP and ORC systems produce about 77.8% and 22.2% of the total electrical energy generation, respectively.
- The conventional system (scenario 1) has the lowest capital cost and the system with integrated CHP and ORC technologies (scenario 3) has the highest capital cost.
- The net operation cost (which includes the summation cost of CO_2 emission, electric power purchase from the grid, OM and fuel cost minus the selling electricity cost to the grid) has the lowest value for case 3 (CHP&ORC) and the highest value for the conventional system.
- Scenario 3 has the lowest CO_2 emission and purchasing electrical energy from the grid among other cases study.
- The CHP system (scenario 2) has an annual total cost saving (compared to the conventional system) with a value of 21.3% and scenario 3 provides an annual total cost saving of 32.3%.
- Scenario 3 (CHP & ORC systems) provides 32.5% saving in CO_2 emission compared to conventional system subsequent case 2 (CHP system) with a value of 9.3%.

Acknowledgment

This work was supported by PERD. Financial support from the Canadian government is gratefully acknowledged. The author would like to thank Mr. Mike Lubun and Mr. Raymond Boulter from Building group at CanmetENERGY Ottawa, Canada for providing thermal load data for the different buildings used in this study and for their value devices and supports. The author is very thankful to Dr. Evgueniy Entchev for his support and advice on this work and Department of Chemical Engineering, University of Waterloo, ON, Canada for kind support on optimization study of this work.

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