IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 14 February 2024, accepted 5 March 2024, date of publication 11 March 2024, date of current version 15 March 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3375336

RESEARCH ARTICLE

Optimal Design of a Decarbonized Sector-Coupled Microgrid: Electricity-Heat-Hydrogen-Transport Sectors

ANSHUL GOYAL, (Graduate Student Member, IEEE), AND
KANKAR BHATTACHARYA, (Fellow, IEEE)
Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada

Corresponding author: Anshul Goyal (a35goyal@uwaterloo.ca)

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

ABSTRACT Benefits accrued by virtue of the presence of microgrids have led to their increased deployment beyond their original objective of supplying power to the remote communities. However, in order to achieve a zero emission energy sector, the challenge is to design a carbon-neutral microgrid. This paper presents a novel, optimal design for a decarbonized microgrid taking into consideration the concept of sector-coupling, by integrating the electric, heat/thermal, hydrogen and transport sectors. The microgrid also includes wind facilities, solar PV panels, green hydrogen system (fuel cells, electrolyzers, storage tanks), Fuel Cell Electric Vehicles (FCEVs) and Battery Energy Storage Systems (BESSs). The real isolated microgrid of Kasabonika Lake First Nation (KLFN) in northern Ontario, Canada, is considered for the design studies and to evaluate the techno-economic feasibility. The effect of (US) Inflation Reduction Act of 2022 (IRA2022) is examined. Results demonstrate the practicability and techno-economic merits of the proposed Decarbonized Sector-coupled Microgrid (DCSCMG). The proposed DCSCMG is compared to the existing diesel-based KLFN microgrid on economic metrics, levelized Cost of Energy (COE) and emissions. Further, the advantages offered by inclusion of BESSs and/or sector-coupling are investigated in the context of net-zero.

INDEX TERMS Battery energy storage system (BESS), decarbonization, electric vehicle (EV), hydrogen, microgrid, sector-coupled system operator (SCSO), sector-coupling.

I. INTRODUCTION

Remote communities around the world have been facing energy access issues, specially access to electricity supply. As per the World Bank and International Energy Agency (IEA), deficiency of energy is a major hindrance for any community's economic growth. It is estimated that around 1.2 billion people globally are deprived of electricity due to their geographical location, lack of infrastructure for connectivity and availability of energy sources, and high energy costs [1]. With the developments in operations and control of microgrid [2], they have been increasingly deployed to supply electricity to many remote communities. Microgrids typically operate in either grid-connected or isolated /off-grid mode. Most of the currently deployed microgrids are high emitters of Green House Gases (GHGs) because of their dependency on emission intensive sources. These microgrids utilize fossil fuel-based generators, mainly diesel, as their main source, with some Renewable Energy Sources (RES) depending on their availability. Therefore, although such microgrids support remote communities' energy access, they are carbon-intensive and poses challenges to meet the net-zero emission targets. Another critical factor for the limited implementation of microgrids is their exorbitantly high cost of electricity in stand-alone usage [3].

Decarbonization in the context of the power sector refers to limiting the GHG emissions from energy generation. Complete decarbonization of a sector is achieved when the net GHG emissions of the sector is zero, referred to as *carbon-neutral system*. Many countries have set a net-zero emissions

The associate editor coordinating the review of this manuscript and approving it for publication was Fabio Massaro.

vision by 2050, including Canada. To support the transition to zero emission, efforts are ongoing to deploy large-scale RES for generation. However, even after their remarkable growth, it still seems impossible to achieve carbon neutrality targets. Thus, there is a need to explore alternative sources of energy and other innovative options to address these issues, for sustainable deployment of microgrids in fulfilling the needs of remote communities of today and the future. Hydrogen is a potential zero-carbon solution to meet the carbon emission reduction targets. Hydrogen is a flexible energy carrier that has significant potential for applications in several fields and is expected to be a ground-breaking technology for a sustainable world [4].

To address the other aforementioned issue of high energy cost in microgrids, an innovative concept of *sector-coupling* has been developed in Germany and now gaining attention worldwide [5]. Sector-coupling on a broader notion is to integrate the operations of various energy end-use and supply sectors such as heating, transportation, power and gas, to provide more flexibility, reliability, adequacy and efficiency to the energy systems. The potential of sector-coupling in reducing the decarbonization cost of the system, is also discussed. Reference [6] provided an overview, challenges and benefits offered by integrated energy systems as compared to the segregated energy sectors. The concept of sector-coupling is critically reviewed in terms of its definition, main purpose, integration aspects, challenges and benefits in [7] and [8]. Apart from techno-economical and environmental barriers, policy and regulatory norms play a crucial role in enabling the feasibility and actual deployment of such systems. The Inflation Reduction Act of 2022 (IRA2022) is one of such initiatives undertaken by the US Department of Energy (DOE) that provides expanded tax credits and incentives to clean energy deployment including RES, Battery Energy Storage Systems (BESSs) and Fuel Cell Electric Vehicles (FCEVs) aimed to achieve climate goals [9]. Standout among various measures under this act is extending Investment Tax Credit (ITC) to include stand-alone Energy Storage Systems (ESSs). Any ESS project with minimum size of 5 kWh is eligible to apply for ITC at 30% until 2032 and thereafter, this percentage decreases.

In [10], HOMER® (Hybrid Optimization Model for Multiple Energy Resources) is used to determine the optimal design of a hypothetical microgrid for various configurations such as diesel-only, RES-only, diesel-RES mixed and break-even distance of microgrid from the grid in grid-connected mode. In [11], an off-grid hybrid energy system is modeled in HOMER® wherein a thermal load controller is deployed to utilize surplus RES generation to produce heat for thermal loads. Although the system considers electric, heat and hydrogen loads, it does not consider the emission aspects, fuel cells or hybrid electric vehicles. Reference [3] investigated the issues of remote communities in northern Ontario, Canada, for electric energy and other RES options to lessen the burden of diesel fuel and to determine their level of penetration into the system. In [12], a Stackelberg game approach is implemented in a electricity and heat sector-coupled system to reduce carbon emissions along with minimizing wind power imbalances through using DR provisions of residential heating. Reference [13] demonstrated the direct and indirect effects of the incentive policies of one sector on another sector, which are coupled. The study investigated the impact of such policies on deployment of EVs for incentives provided on RES generation and vice-versa. In [14], the technical feasibility and economic viability of a multi-sectoral (power, heat, transport and desalination) energy system, supplied by 100% RES, is examined. It considered the coupling of various sectors through electrification using power-to-X processes and presented pathways of achieving low-cost energy in a sustainable manner. Reference [15] presented a techno-economic analysis of a hydrogen integrated energy system which comprised RES, on-site hydrogen production through electrolysis, refuelling station and hydrogen-fuelled vehicles consumption. The analysis highlighted the potential of hydrogen as an alternative fuel to existing carbon-intensive fuels. In [16], different modeling and solution methods are examined to optimize the operation of integrated electricity and heat systems. The system explored the operation under uncertainty, impact of joint dispatch of electricity and heat systems, joint market clearing of both these systems, *etc.*, to determine the optimal operation. Reference [17] investigated the role of different ESSs (excluding hydrogen-based systems) in reducing carbon emissions in a sector-coupled (electricity, heat and transport) system. The paper highlighted that implementing sector-coupling aided in achieving European carbon emissions reduction targets and can delay the need for large storage capacities, thus providing time to further develop more efficient ESSs.

It can be noted from the literature review that most of the works have explored the role of RES penetration, benefits offered by microgrid deployment and merits of sector-coupling in meeting the ongoing issues, either individually or in context of hypothetical case studies. Further, the reported works have mostly evaluated integration of fewer resources at a time. To the best of the authors' knowledge, no work has been reported so far, investigating the performance of a real microgrid which is carbon-neutral and designed based on sector-coupling concept, with consideration of FCEVs and green hydrogen system. It is envisaged that to meet the current challenges in a sustainable manner, the simultaneous inclusion of multiple resources and coupling of different sectors need be formulated and studied in detail; as each resource has its own merits and limitations (*there is no one fit for all*). Thus, there is a need to develop a decarbonized microgrid comprising the state-of-art technologies such as BESSs, FCEVs, green hydrogen systems, *etc.*, designed on sector-coupling concept, to address the aforementioned issues.

Based on the above discussions and hypothesis, the main objectives of this paper are:

- Develop a generic architecture of a microgrid wherein different sectors such as electricity, heat, hydrogen

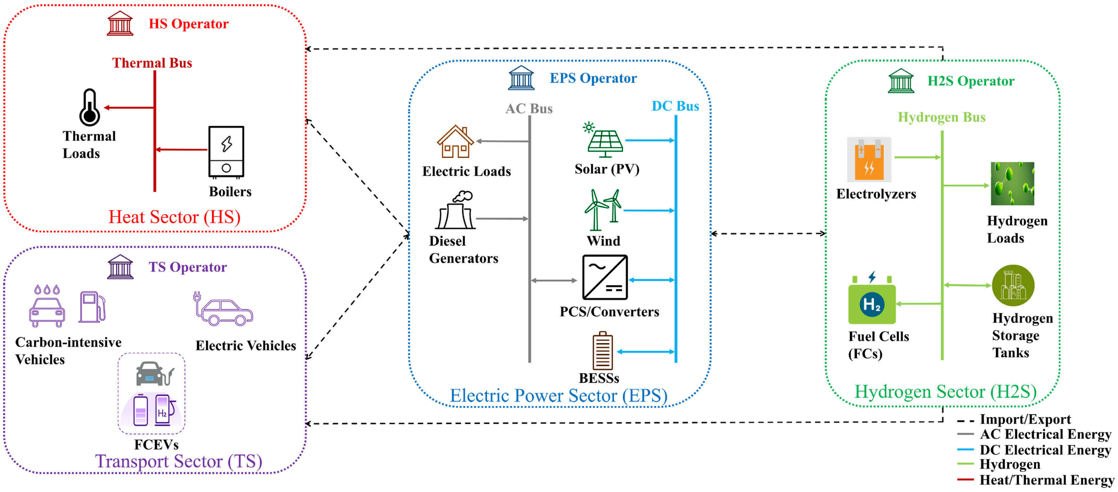


FIGURE 1. Schematic of different sectors (without *sector-coupling*).

and transport are integrated and operated by a single operator to achieve a net-zero system. This proposed Decarbonized Sector-coupled Microgrid (DCSCMG) will include wind facilities, solar PV panels, FCEVs, BESSs and green hydrogen systems comprising electrolyzers, storage tanks and fuel cells.

- Determine the optimal design of the DCSCMG with realistic inputs of locational, operational and economic characteristics, and techno-economic models of different components (BESSs, FCEVs, electrolyzers, fuel cells, RES) for a real isolated microgrid in northern Canada.
- Examine the impact of inclusion of BESS on economic metrics, levelized Cost of Energy (COE), total emissions and fuel consumption.
- Investigate the effect of sector-coupling, considering the electricity, heat, hydrogen and transport sectors, on economic metrics, levelized COE, total emissions and fuel consumption of the DCSCMG.
- Examine the impact of the rebate offered through IRA2022 on the deployment of various resources and the economic metrics of the DCSCMG.
- Investigate the effect of simultaneous inclusion of BESS, sector-coupling, decarbonization strategy and IRA2022 rebate on the design of DCSCMG, in combination of two, three or all of them together.
- Evaluate the effect of fuel price variations and limits on emissions, on the optimal design configurations and cost parameters of the DCSCMG.

The main contributions of this work are as follows:

- A novel architecture of a realistic and futuristic DCSCMG is proposed which integrates multiple sectors (electricity, heat, hydrogen and transport) using the sector-coupling concept.
- The proposed architecture helps to achieve a net-zero emission microgrid.
- The presented work will help policy makers, investors, microgrid operators and planners to develop a comprehensive policy on achieving a carbon-neutral energy ecosystem through a set of implementable decisions which have been demonstrated using practical case studies.

The rest of the paper is organized as follows: Section II presents the overall schematic of the proposed DCSCMG and Section III describes the design and modeling of different components of the DCSCMG. Case studies, results and analysis are presented in Section IV while Section V draws the main conclusions.

II. ARCHITECTURE OF A DECARBONIZED MICROGRID BASED ON SECTOR-COUPLING

Consumers have different energy requirements in their day-to-day life which has led to the development of various sectors such as heat, transport, electricity, hydrogen, *etc.* To cater the consumers' needs, these sectors are generally operated by their respective operators. Any sector operator's primarily role is to ensure demand-supply balance for its system. Generally, the different sectors communicate with each other based on contracts or import/export trading where each sector operator has minimal information of the other sectors involved in the trade. Fig. 1 illustrates the schematic of different sectors considered in this paper, wherein each sector is individually settled by its respective operator with import/export from other sectors. This kind of mechanism is followed by many countries across the globe however, with the advancement of smart grids and microgrids, and development of power-to-X technologies, there is a shift towards the new concept where an integrated system comprised of different sectors are settled by a single operator, termed as sector-coupling (Fig. 2).

The primary role of a *Sector-Coupled System Operator (SCSO)* is similar to that of a typical system operator *i.e.* to maintain the demand-supply balance and operate the system

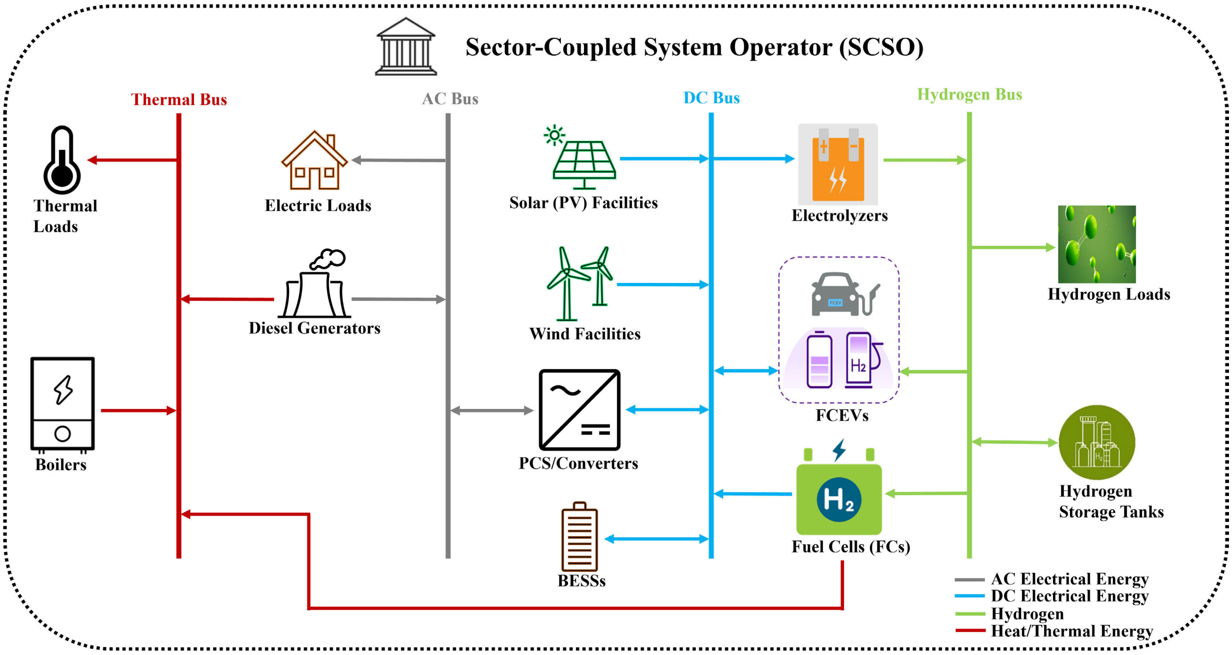


FIGURE 2. Architecture of sector-coupled microgrid.

reliably. In case of sector-coupling, the SCSO ensures the balance and reliability of the integrated system which is formed by coupling different sectors (Fig. 2). The SCSO has access to information from each sector being coupled and operates them as an integrated system for dispatching and meeting the demands of different fuel-types of loads. Contrary to the conventional structure where individual sectors are operated by their respective system operators (Fig. 1), the SCSO introduces many advantages such as provision for more flexible resources, greater social welfare, more robust approach towards uncertainties, better utilization of resources, lower prices, higher probability of achieving decarbonization across sectors for a net-zero system, etc. [18], [19], [20], [21], [22].

In this paper, a carbon-neutral microgrid based on the sector-coupling concept is proposed that caters to today's complex energy needs in a sustainable manner. The proposed DCSCMG includes conventional components of a microgrid such as solar, wind, diesel generators, electric loads, Combined Heat and Power (CHP) diesel units, fuel cells, BESSs, thermal loads and converters, along with the addition of state-of-art resources such as hydrogen loads, hydrogen storage, hydrogen production (electrolyzers), CHP hydrogen fuel cells and FCEVs (as shown in Fig. 2). In contrast to the former where each sector is managed by different system operators, a sector-coupled system is managed by a single system operator facilitating more flexibility, adequacy, resiliency, dispatch of low or zero-emission resources and reduced overall cost.

The existing isolated microgrid of Kasabonika Lake First Nation (KLFN) in northern Ontario, Canada, has been considered in this work to model the proposed DCSCMG. To demonstrate the effect of sector-coupling, various different sectors are integrated, as illustrated in Fig. 2, where different buses (ac bus, dc bus, hydrogen bus and thermal bus) are classified depending upon the kind of resources and loads connected. In order to take into account the electrification of the transport sector, which is being encouraged globally, FCEVs are also modeled in the proposed system. The potential of green hydrogen system as an alternative to fossil fuel-based sources is examined through various case studies. The impact of regulatory policies such as IRA2022, on the overall system configuration, sizing, economics and time-frame for achieving carbon neutrality are also investigated.

III. DCSCMG MODELING AND SIMULATION

Software tools such as HOMER®, iHOGA®, Hybrid2®, RETScreen®, *etc.* has been used to simulate and optimize isolated hybrid energy systems [11]. In this paper, HOMER Pro® [23], developed by National Renewable Energy Laboratory, USA, is used for its suitability to optimize microgrids incorporating components' physical factors and providing provisions of integrating multiple sectors. The components of DCSCMG (as shown in Fig. 3) are modeled as follows:

A. DIESEL GENERATORS

The component library of HOMER Pro® provides generators' models with information on fuel type, emission factors, fuel curve data, Operation and Maintenance (O&M) schedule, and cost parameters pertaining to capital/initial, replacement and O&M. Site specific inputs can also be considered to make the model more realistic, such as

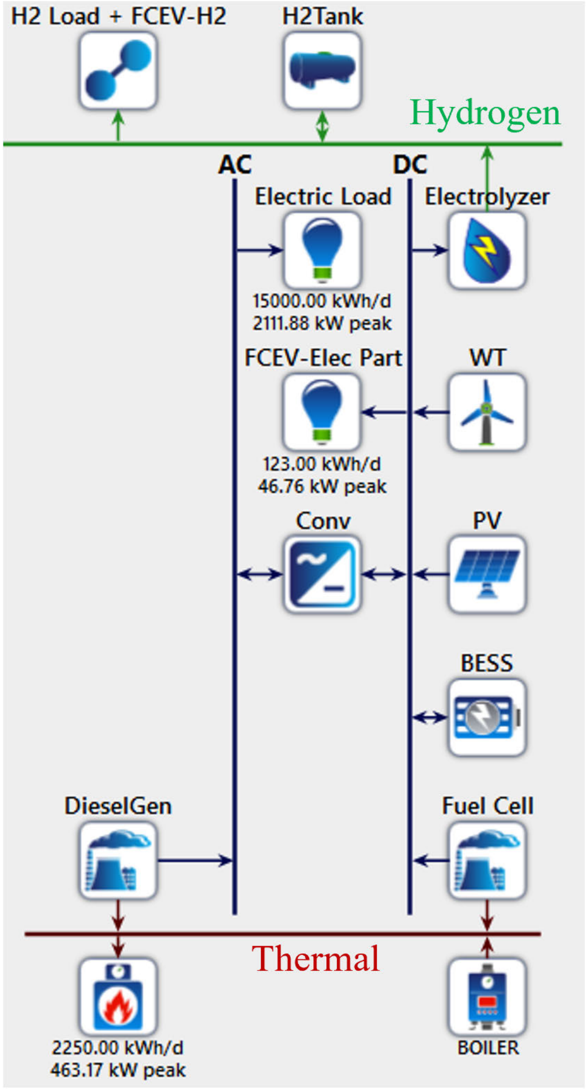


FIGURE 3. **HOMER model of decarbonized sector-coupled microgrid.**

minimum run-time, fuel price, lifetime, CHP recovery fraction, minimum load ratio and initial hours of operation.

B. SOLAR PV AND WIND FACILITIES

The solar PV components in HOMER Pro® can represent both flat panel and concentrating PV systems. It allows users to define the cost parameters, derating factor and size. The wind turbine models in HOMER Pro® allow users to specify power curve, turbine losses, maintenance tasks, downtime, lifetime, hug height and cost parameters [11]. Realistic locational data on temperature, solar radiation and wind speed (of KLFN), obtained from NASA Prediction of Worldwide Energy Resource, are considered in this paper.

C. ELECTRIC, HYDROGEN AND THERMAL LOADS

Electric loads can be simulated in HOMER Pro® by defining peak month, load profile (residential, commercial, industrial, community or user-defined), scaling factor, *etc*. In this work, total daily average electricity demand and peak power data obtained from [1] for KLFN, an Oji-Cree First Nation community in northern Ontario, Canada, is considered. The load profile simulated in this paper for KLFN is considered to be community type (Fig. 4(a)). The hydrogen load (Fig. 4(d)) can be modeled by choosing load profile, peak month, metrics such as average and peak hydrogen demand, unmet hydrogen and/or penalty. Thermal loads are defined by load profile, peak month, average and peak requirement. The thermal load is assumed to be 15% of the electric demand of the KLFN community (Fig. 4(b)). Different supply options such as boiler, and waste heat recovery supply from diesel generator and fuel cell are considered.

D. ELECTROLYZERS AND HYDROGEN STORAGE

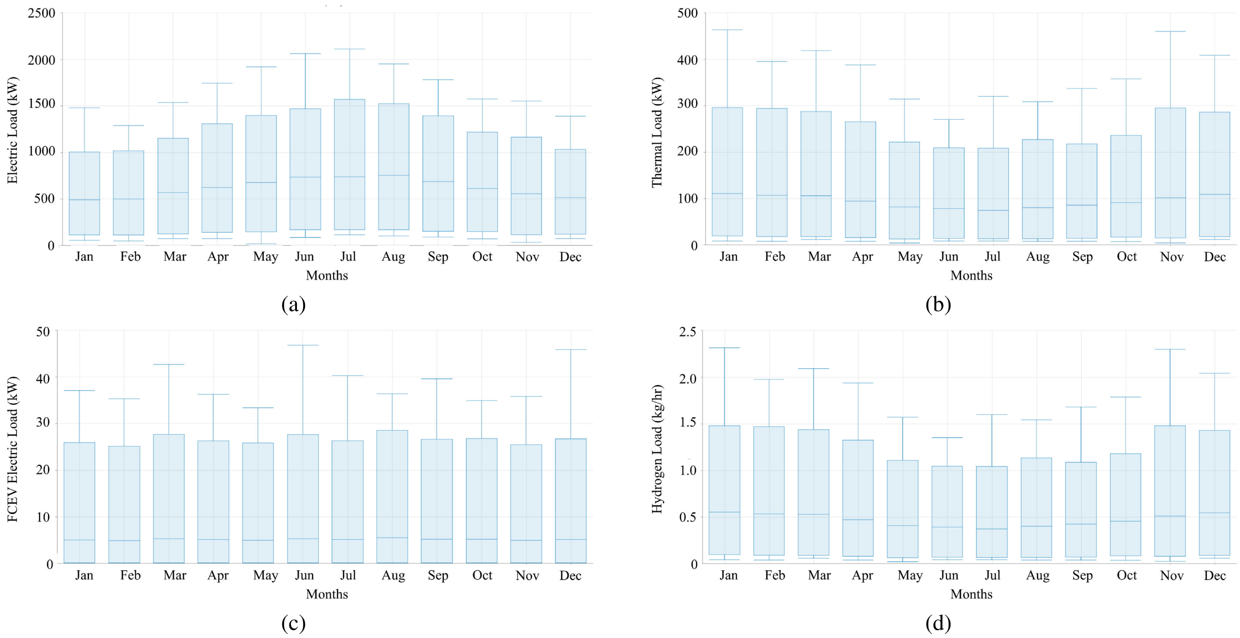
The component library of HOMER Pro® contains models of the electrolyzer where users can define the capacity, lifetime, efficiency, minimum load ratio, schedule and cost parameters pertaining to capital, replacement and O&M. Hydrogen tanks can be modeled by entering information of initial tank level, different capacities and cost components.

E. FUEL CELLS

HOMER Pro® has a provision for a fuel cell of 250 kW fixed capacity. This model allows users to define the fuel type, emission factors, fuel curve data, O&M schedule and cost parameters. Other inputs include minimum run-time, fuel price, lifetime, CHP recovery fraction, minimum load ratio and initial hours of operation. However, since the objective of this paper is to determine the optimal design of the DCSCMG, the fixed capacity fuel cell model was replaced by a diesel generator and changing its attributes to that of a fuel cell and the fuel type from diesel to hydrogen, to obtain a variable size fuel cell. Such a customized design of fuel cell allows to optimally size the fuel cell based on the system under study. Different types of fuel cells such as polymer electrolyte membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), *etc.* can be modeled by defining their characteristics in the user-defined parameters using the proposed approach.

F. FUEL CELL ELECTRIC VEHICLES (FCEVS)

HOMER Pro® does not provide any built-in model for FCEVs or any kind of EVs. To design a futuristic and generic microgrid, the effect of EV penetration into the microgrid needs to be considered. To this effect, the FCEVs were modeled considering the battery as an electric load while the fuel cell as hydrogen load. The electric load was estimated considering Level2 charging of EVs at 4 charging stations, each 12 kW rated, with varying frequency of fleet in a day for various months over a year. Similarly, the fuel cell was simulated by considering varying hydrogen load in likewise pattern. The FCEVs electrical (Fig. 4(c)) and hydrogen loads (Fig. 4(d)) are designed based on the model available in HOMER Grid® software.



(a) (b) (c) (d)

FIGURE 4. Monthly profiles of different kinds of loads: (a) Electric load profile (b) Thermal load profile (c) FCEV electric load profile (d) Hydrogen load profile.

G. POWER CONVERSION SYSTEM (PCS)/CONVERTERS

The proposed DCSCMG comprises both dc and ac elements and thus Power Conversion System (PCS) is required for their coupling. HOMER Pro® allows to define the following design values for PCS: lifetime, efficiencies for inverter/rectifier modes, capacities and cost parameters.

H. BATTERY ENERGY STORAGE SYSTEMS (BESSS)

HOMER Pro® provides various options to accommodate a range of BESS models. The physical and thermal characteristics of the BESS are represented using a modified kinetic storage model of Li-Ion type batteries. Such models include temperature dependency on capacity and temperature effects on calendar degradation, cycling lifetime estimation using Rainflow Counting algorithm and rate dependent losses apart from general parameters such as initial state-of-charge (SOC), minimum SOC and degradation limit. The differential equations governing the maximum power that the BESS can charge and discharge are given in [11]. The actual temperature effects from the KLFN region are considered while designing the optimal BESS.

IV. RESULTS AND DISCUSSIONS

The models are simulated in HOMER Pro® [23] and the performances are tested on the real isolated microgrid of KLFN in northern Ontario, Canada. Different cases and scenarios are developed to determine the optimal design of the proposed DCSCMG, and to examine the effect of incorporating BESS, sector-coupling, decarbonization strategy and incentives such as IRA2022. Table 1 presents an overview of the two scenarios and eight cases considered in this work along with the scenarios & cases configurations and their respective descriptions. The technical, operational and financial data of various components of the DCSCMG considered, are presented in Table 2 and Table 3 [3], [10] and [11]. The DCSCMG operational lifetime is considered to be 20 years, inflation rate of 3%, discount rate of 6%, diesel price of 1.05 \$/L and hydrogen price of 1.58 \$/L. For Case-8 which considers IRA2022, the minimum offered incentive of 30% is considered for examining the impact.

A. DEVELOPMENT OF SCENARIOS AND CASES

Two scenarios are considered wherein in Scenario-1, fixed (existing) capacity of RES in the KLFN microgrid, *i.e.* 263 kW and 30 kW for solar and wind, respectively are considered. While in Scenario-2, the optimal sizing of all components of the DCSCMG including RES (soalr and wind), with their associated lower and upper bounds, are obtained. For both these scenarios, eight cases are performed to fulfill the objectives of this paper as outlined in the Section I. Case-1 corresponds to the base system (representing Business As Usual (BAU)) without inclusion of BESS, sector-coupling, IRA2022 rebate or decarbonization strategy. Case-2, Case-3 and Case-4 represents the system wherein the Base have been modified to include BESS, sector-coupling and decarbonization strategy, respectively, one at a time. Thereafter, Case-5 and Case-6 correspond to the cases in which two out of these three features are included together, i.e. Case-5 consists of BESS and sector-coupling integration while Case-6 incorporates BESS and decarbonization strategy together. Case-7 represents a system wherein all three features are considered simultaneously, while Case-8 additionally includes the ITC rebate offered under IRA2022.

TABLE 1. Scenarios and case studies: their configurations and corresponding descriptions.

Scenarios	Scenario Configuration	Scenario Description
Scenario-1	Optimal DCSCMG with existing RES	Fixed RES capacity = Existing RES capacity
Scenario-2	Optimal DCSCMG with optimal RES	Optimal RES capacity $\geq$ Existing RES capacity
Cases	**Case Configuration**	**Case Description**
Case-1	Base (w/o decarbonization/sector-coupling/BESS)	Only EPS considered without BESS
Case-2	Base + BESS	EPS with BESS considered
Case-3	Base + Sector-coupling	All sectors considered without BESS or Fuel cells
Case-4	Base + Decarbonization	EPS w/o BESS, Fuel cells replacing Diesel Gen
Case-5	Base + Sector-coupling + BESS	All sectors + BESS, no Fuel cells
Case-6	Base + Decarbonization + BESS	EPS + BESS, Fuel cells replacing Diesel Gen
Case-7	Base + Decarbonization + Sector-coupling + BESS	All sectors + BESS, Fuel cells replacing Diesel Gen
Case-8	Case-7 + IRA2022	Case-7 with inclusion of IRA2022 (30% ITC)

TABLE 2. Technical design input [3], [10] and [11].

Component	Details
BESS	Initial SOC=40%, Min. SOC=20%, Degradation limit=40%
Converter	Efficiency=85%
Diesel Generator	CHP Heat Recovery Ratio=25%, Min. Load Ratio=25%, Min. Runtime=30 min, Fuel=1.05 \$/L
Electric Load	Average=15,000 kWh/day, Peak=2111.8 kW, Load Factor=0.3, Community Type
Electrolyzer	Efficiency=85%
Fuel Cell	CHP Heat Recovery Ratio=25%, Min. Load Ratio=25%, Min. Runtime=0 min, H_2 Fuel=1.58 \$/L
FCEV (Electric Load)	Average=123 kWh/day, Peak=5.13 kW, Load Factor=0.11, Level2
Hydrogen Load	Average=11.25 kg/day, Peak=2.32 kg/hr, Load Factor=0.2, FCEV H_2 Part & other H_2 Loads
Hydrogen Tank	Initial Tank Level=20%
Solar PV	Derating Factor=80%
Wind Turbine	Hub Height=24 m
Thermal Load & Boiler	Average=2250 kWh/day, Peak=463.17 kW, Load Factor=0.2, Efficiency=85%

TABLE 3. Financial design input [3], [10] and [11].

Component	Capital Cost	Replacement Cost	O&M Cost	Lifetime
BESS	650 \$/kWh	650 \$/kWh	13 \$/kWh/year	365 cycles/year for 20 years
Converter	300 \$/kW	240 \$/kW	30 \$/kW/year	20 years
Diesel Generator	500 \$/kW	400 \$/kW	0.84 \$/kW/operating hr	90,000 hrs
Electrolyzer	5000 \$/kW	5000 \$/kW	50 \$/kW/year	20 years
Fuel Cell	1000 \$/kW	1000 \$/kW	1 \$/kW/operating hr	90,000 hrs
Hydrogen Tank	574 \$/kg	574 \$/kg	50 \$/kg/year	20 years
Solar PV	8365 \$/kW	6692 \$/kW	42 \$/kW/year	20 years
Wind Turbine	13414 \$/kW	10731 \$/kW	335 \$/kW/year	20 years

B. EFFECT OF INCLUSION OF BESS

Fig. 5 presents the Net Present Cost (NPC), capital cost and O&M cost, while Fig. 6 illustrates the levelized COE and emissions amount for various cases and scenarios. For Scenario-1, it can be observed that the NPC (Fig. 5(c)), levelized COE (Fig. 6(a)) and emissions (Fig. 6(b)) in Case-2 are reduced by about 28% with the optimal BESS capacity as compared to Case-1 although the capital cost is quadrupled (Fig. 5(a)). Similarly for Scenario-2, these factors in Case-2 are reduced by more than 44% as compared to Case-1 with inclusion of optimal BESSs while the capital cost increased twelve-fold. The reductions in NPC, levelized COE and emissions can be attributed to the decrease in operating hours of diesel generators in Case-2 due to the utilization of the energy stored in BESSs.

A similar effect of the BESS inclusion can be observed while comparing Case-5 over Case-3 and Case-6 over Case-4 for both scenarios, wherein it is noted that the levelized COE reduces in Case-5 and Case-6 over Case-3 and Case-4, respectively, when BESS with sector-coupling is introduced and interestingly, even the decarbonized microgrid with BESS yields a lower levelized COE as compared to the existing microgrid in both scenarios. However, it will still be higher in comparison to Case-2 because of inclusion of clean sources.

Fig. 7 presents the quantities of fuels (diesel and hydrogen) consumed in each case under different scenarios. It is noted that in Case-2 the consumption decreased significantly as compared to Case-1, in both scenarios because of BESSs. During surplus RES generation, the BESSs store the excess energy via charging operation while during peak demand periods they supply the stored energy through discharging operation. It can be observed that consumption of fuels are lower in Scenario-2 in all cases compared to Scenario-1. This is mainly due to the increased capacity of RES being available in Scenario-2 due to optimal design.

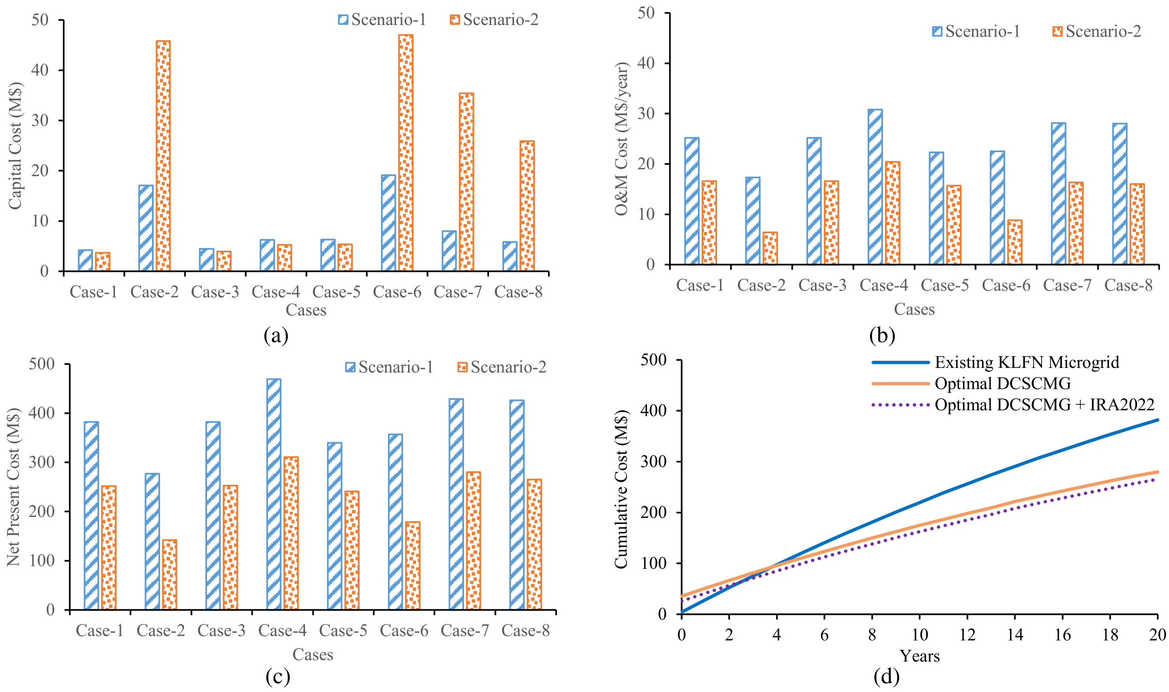


FIGURE 5. Cost comparisons for different scenarios and cases: (a) Capital cost (b) O&M cost (c) Net present cost (d) Cumulative cost.

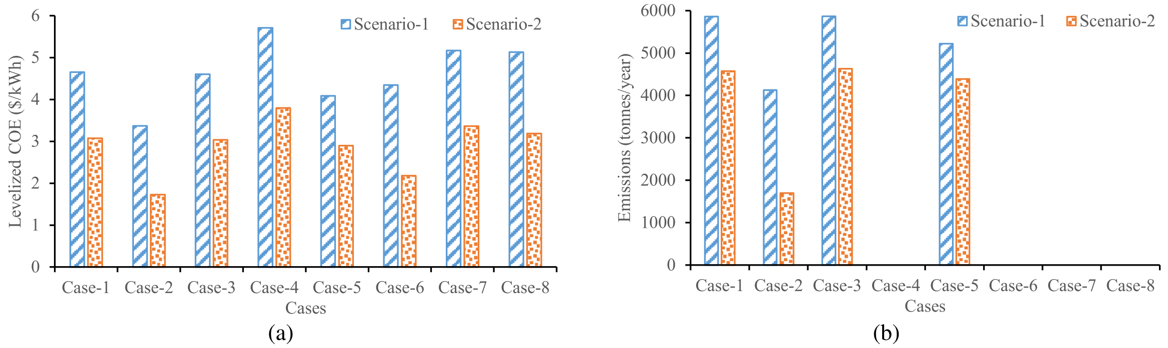


FIGURE 6. Comparison of energy cost and emissions: (a) Levelized cost of energy (b) Emissions.

C. EFFECT OF SECTOR-COUPLING AND/OR DECARBONIZATION

Comparison of Case-3 and Case-4 over Case-1 shows that the adoption of sector-coupling reduces the levelized COE, whereas decarbonization of the microgrid leads to its increase in both scenarios, due to the deployment of the clean but costlier energy sources in the latter (Fig. 6(a)). This increased cost is a good trade-off with the achieved GHG emissions reduction of 6,000 tonnes per year in Scenario-1 and 4,600 tonnes per year in Scenario-2 (Fig. 6(b)). And the increase in capital (Fig. 5(a)) and O&M (Fig. 5(b)) costs were not significant. In Scenario-1, the decarbonization cases (Case-4, 6, 7 & 8) consider the replacement of existing diesel generator with a fuel cell of at least the same capacity. While in Scenario-2, the decarbonization cases are formulated considering the replacement of existing diesel generator with optimal sized fuel cell.

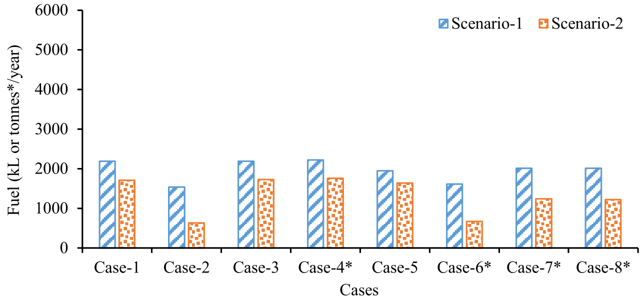
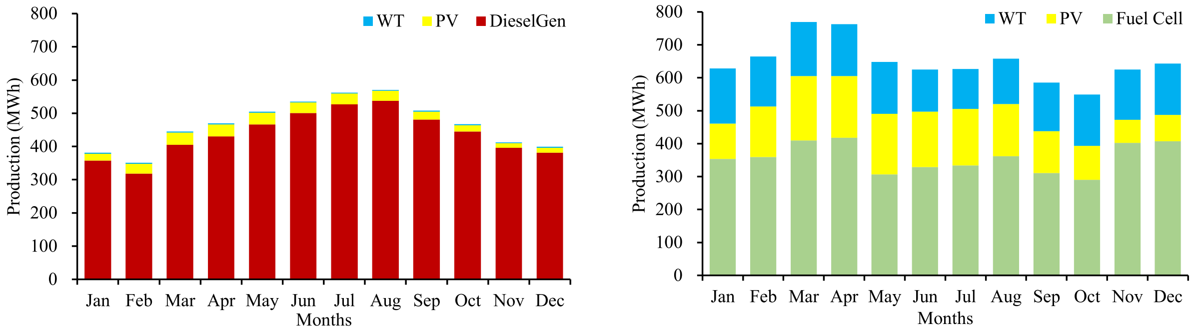


FIGURE 7. Fuel consumption (diesel+hydrogen).

Case-7 results show that the levelized COE are higher as compared to Case-6 (Fig. 6(a)), but for a fair comparison, if the cost of fuel used in other sectors such as heating, transportation, *etc.* are considered, then Case-7 cost will be lower than Case-6 in both scenarios. Moreover, the capital



(a)

(b)

FIGURE 8. **Comparison of generation mix: (a) Existing KLFN microgrid (b) Proposed KLFN DCSCMG.**

cost is lower as compared to Case-6 (Fig. 5(a)). Further, it can be noted that implementing sector-coupling approach reduced the overall consumption of fuels (Case-3, 5, 7 & 8). This effect can be more predominantly visible if the fuels consumption of other sectors in an uncoupled scenarios are taken into account.

It is noted that the levelized COE reduced by 6.34% in Scenario-1 and 8.84% in Scenario-2 when the sector-coupling was included (Case-3 as compared to Case-1). Whereas, the levelized COE increased by 16.26% in Scenario-1 and 13.93% in Scenario-2 when the decarbonization strategy was implemented (Case-4 as compared to Case-1). This effect was damped by the inclusion of sector-coupling and BESS in the decarbonization strategy wherein the levelized COE increased by only 5.24% in Scenario-1 and 0.98% in Scenario-2 (Case-7 compared with Case-1). This increase was further damped by inclusion of IRA2022 rebate, 4.52% in Scenario-1 and -4.31% in Scenario-2 (Case-8 compared with Case-1). The inclusion of sector-coupling led to notable decrease in the system emissions, which reduced by 30.96% in Scenario-1 and 30.24% in Scenario-2 (Case-3 compared with Case-1).

D. COMPARISON ANALYSIS: BAU VS OPTIMAL DCSCMG

While the mix of energy supply capacity options are obtained for all cases and scenarios, due to brevity, the results are presented for Case-1 of Scenario-1 denoting the existing KLFN microgrid (Fig. 8(a)) and Case-7 of Scenario-2 which reflects the optimal design of the proposed DCSCMG (Fig. 8(b)). These two systems are particularly selected for discussion to analyze the effect of deployment of various energy supply options in achieving a transition from a carbon-intensive system to the carbon-neutral. It can be noted that the fuel cell replaces diesel generator for a decarbonized system, and the total generation of Fig. 8(b) is more as compared to that of Fig. 8(a) because Fig. 8(b) corresponds to Case-7 which considers the impact of sector-coupling and energy storage (BESSs). Both the curves differ in their overall pattern because the DCSCMG comprises multiple sectors which have their respective peaks at different time of the year. It is noted that the levelized COE decreased by 31.52%.

E. EFFECT OF IRA2022: REBATE VIA ITC

With the consideration of IRA2022, the costs further reduce in Case-8 as compared to Case-7. Fig. 5(d) illustrates the cumulative cost incurred by three systems: Case-1 of Scenario-1 (existing KLFN microgrid), Case-7 (optimal DCSCMG) and Case-8 (optimal DCSCMG with IRA2022) of Scenario-2. In the initial years the proposed DCSCMGs incur more cash requirement compared to the base system but over the project life, the DCSCMG optimal designs are more cost-effective with net-zero emissions. Note that inclusion of IRA2022 further reduces the payback period, indicating that such incentives can promote decarbonization with marginal increase in cost from the base case, leading toward achieving carbon-neutrality targets. The rise in levelized COE was limited by inclusion of IRA2022 rebate wherein the levelized COE increased only by 4.52% in Scenario-1 and -4.31% in Scenario-2 (Case-8 compared with Case-1) in contrast to 5.24% and 0.98%, respectively when it is not included (Case-7 over Case-1).

Table 4 summarizes the results obtained for all eight cases under both scenarios.

F. EFFECT OF FUEL PRICE VARIATIONS AND EMISSIONS LIMITS

The effect of two important parameters, hydrogen fuel price and emissions cap, are examined to evaluate their impact on achieving a carbon-neutral system. The sensitivity analyses examine the impact of hydrogen fuel price on NPC and determines the relationship between NPC, levelized COE and emissions, respectively.

Fig. 9 shows the impact of hydrogen fuel price variations on the NPC and fuel cells' operating hours for Case-7, Scenario-2. This case corresponds to the proposed DCSCMG for KLFN community and is simulated by increasing/decreasing the hydrogen fuel price by 5% and 10% in both directions of its base value (1.58 $/L). Increasing the fuel price resulted in increase in the NPC and operating hours of fuel cells. However, the impact of decreasing the fuel price on the NPC is not significant because the optimal sizes of fuel cells, electrolyzers and tanks obtained at the base price,

TABLE 4. Optimal design configurations of KLFN microgrid.

Cases	Diesel Gen (kW)	Solar PV (kW)	Wind (kW)	BESS (kWh)	Electrolyzer (kW)	Hydrogen Tank (kg)	Fuel Cell (kW)
Scenario-1: Optimal DCSCMG with existing RES							
Case-1	3100	263	30	-	-	-	-
Case-2	3100	263	30	19738	-	-	-
Case-3	3100	263	30	-	50	10	-
Case-4	-	263	30	-	-	-	3100
Case-5	3100	263	30	1099	250	50	-
Case-6	-	263	30	19738	-	-	3100
Case-7	-	263	30	777	200	50	3100
Case-8	-	263	30	777	200	50	3100
Scenario-2: Optimal DCSCMG with optimal RES							
Case-1	2000	263	30	-	-	-	-
Case-2	2000	1400	1500	19528	-	-	-
Case-3	2000	268	30	-	50	50	-
Case-4	-	263	30	-	-	-	2000
Case-5	2000	291	40	408	200	50	-
Case-6	-	1400	1500	19317	-	-	2000
Case-7	-	1392	1400	1240	200	50	2000
Case-8	-	1400	1400	1318	250	50	2000

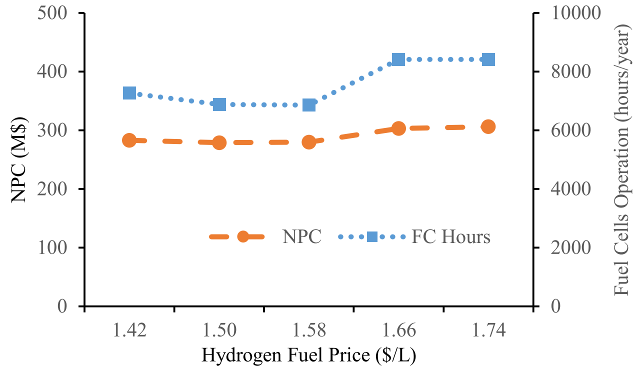


FIGURE 9. Effect of hydrogen fuel price variations.

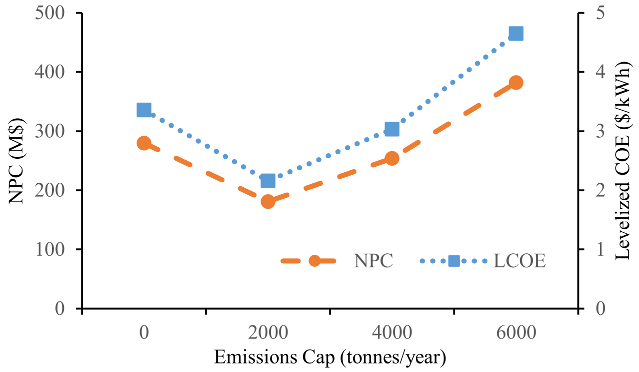


FIGURE 10. Effect of emissions cap.

are already at their maximum capacity. The NPC would have been impacted if other cheap, carbon-neutral resources were available to reduce the burden on the hydrogen system or if the upper limits of the hydrogen system components were relaxed.

Fig. 10 presents the effect of changing the emissions cap on the NPC and levelized COE. The zero emissions system corresponds to the DCSCMG optimal design (Case-7, Scenario-2) while the existing configuration of KLFN microgrid (6000 tonnes/year) corresponds to Case-1, Scenario-1 and is the most emission producing configuration. It can be observed that the NPC and the levelized COE follows the same pattern with respect to the emission caps. The other two intermediate emission cap data points in the figure corresponds to optimal configurations considering sector-coupled system with provision of optimal sizing of RES (solar PV and wind) and BESSs. The NPC and levelized COE increases with the emissions cap in these two designs due to the fact that components sizes (diesel generator and fuel cells) available for optimizing increases in discrete steps of 500 kW. This results in oversizing of the components and causing higher NPC and levelized COE than expected in case of increased emissions cap. Such results are purposely illustrated here to show the effect of realistic component sizing limitation over usual theoretical engineering economics. However, it can be concluded that a decarbonized system is achievable at a higher NPC and levelized COE. This additional cost can be reduced by incorporating the concept of sector-coupling along with BESSs and by providing incentives for cleaner resources.

V. CONCLUSION

In this paper, a novel, generic and futuristic architecture for a decarbonized microgrid, taking into consideration the concept of sector-coupling, by simultaneously integrating electric, thermal, transportation and hydrogen loads, was presented. The proposed DCSCMG comprised RES, FCEVs, BESSs, electrolyzers, storage tanks and fuel cells. The real isolated microgrid of KLFN was considered for the studies. The impact of inclusion of BESS, sector-coupling, decarbonization strategy and IRA2022 rebate, individually or in combination of two, three or all of them together, are examined by various cases studies. These case studies analyzed their impact on techno-economic metrics, levelized cost and total emissions. The inclusion of BESS resulted in significant decrease in fuels (diesel and hydrogen) consumption in both scenarios and also assisted in reducing the levelized COE and system emissions. The results indicated that the inclusion of sector-coupling in the microgrid assisted in reducing levelized COE by 6.34% in existing KLFN microgrid and 8.84% in the optimal design. While the decarbonization strategy of replacing diesel-fed generators with fuel cells led to increase in levelized COE by 13.93% in optimal design which was damped to 0.98% only with the inclusion of sector-coupling and BESS. Further, it was reduced when the rebate offered under IRA2022 was considered, denoting the acceleration of achieving net-zero emission goal. The outcomes showed that the decarbonization of the energy system of a community is achievable more economically, reliably and feasibly by deploying green hydrogen system with energy storage in a sector-coupled microgrid design (DCSCMG).

REFERENCES

[1] M. Arriaga, C. A. Caizares, and M. Kazerani, "Long-term renewable energy planning model for remote communities," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 221–231, Jan. 2016.

[2] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of AC microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[3] M. Arriaga, C. A. Cañizares, and M. Kazerani, "Renewable energy alternatives for remote communities in northern Ontario, Canada," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 661–670, Jul. 2013.

[4] A. Körner, C. Tam, S. Bennett, and J. Gagné, "Technology roadmap-hydrogen and fuel cells," Int. Energy Agency, Paris, France, Tech. Rep., 2015.

[5] L. V. Nuffel, J. G. Dedecca, T. Smit, and K. Rademaekers, "Sector coupling: How can it be enhanced in the EU to foster grid stability and decarbonise," Study requested by ITRE Committee PE, Brussels, Belgium, Tech. Rep., 2018, vol. 626.

[6] J. Wu, J. Yan, H. Jia, N. Hatziargyriou, N. Djilali, and H. Sun, "Integrated energy systems," *Appl. Energy*, vol. 167, pp. 155–157, Apr. 2016.

[7] J. Ramsebner, R. Haas, A. Ajanovic, and M. Wietschel, "The sector coupling concept: A critical review," *WIREs Energy Environ.*, vol. 10, no. 4, p. e396, Jul. 2021.

[8] G. Fridgen, R. Keller, M.-F. Körner, and M. Schöpf, "A holistic view on sector coupling," *Energy Policy*, vol. 147, Dec. 2020, Art. no. 111913.

[9] Inflation Reduction Act of 2022. (2022). *Congressional Record*. [Online]. Available: https://www.energy.gov/lpo/inflation-reduction-act-2022

[10] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renew. Energy*, vol. 45, pp. 7–15, Sep. 2012.

[11] M. R. Akhtari and M. Baneshi, "Techno-economic assessment and optimization of a hybrid renewable co-supply of electricity, heat and hydrogen system to enhance performance by recovering excess electricity for a large energy consumer," *Energy Convers. Manage.*, vol. 188, pp. 131–141, May 2019.

[12] A. A. Bashir, A. Lund, M. Pourakbari-Kasmaei, and M. Lehtonen, "Minimizing wind power curtailment and carbon emissions by power to heat sector coupling—A Stackelberg game approach," *IEEE Access*, vol. 8, pp. 211892–211911, 2020.

[13] M. Esmaeili, A. Anvari-Moghaddam, S. M. Muyeen, and V. S. Peric, "On the role of renewable energy policies and electric vehicle deployment incentives for a greener sector coupling," *IEEE Access*, vol. 10, pp. 53873–53893, 2022.

[14] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. De Souza Noel Simas Barbosa, M. Fasihi, S. Khalili, T. Traber, and C. Breyer, "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," *Energy*, vol. 227, Jul. 2021, Art. no. 120467.

[15] S. Nistor, S. Dave, Z. Fan, and M. Sooriyabandara, "Technical and economic analysis of hydrogen refuelling," *Appl. Energy*, vol. 167, pp. 211–220, Apr. 2016.

[16] M. Zhang, Q. Wu, J. Wen, Z. Lin, F. Fang, and Q. Chen, "Optimal operation of integrated electricity and heat system: A review of modeling and solution methods," *Renew. Sustain. Energy Rev.*, vol. 135, Jan. 2021, Art. no. 110098.

[17] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, "The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system," *Energy Convers. Manage.*, vol. 201, Dec. 2019, Art. no. 111977.

[18] Z. Ji and X. Huang, "Day-ahead schedule and equilibrium for the coupled electricity and natural gas markets," *IEEE Access*, vol. 6, pp. 27530–27540, 2018.

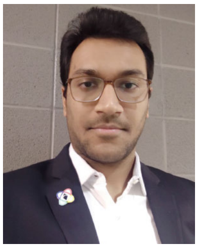
[19] M. J. Brear, R. Baldick, I. Cronshaw, and M. Olofsson, "Sector coupling: Supporting decarbonisation of the global energy system," *Electr. J.*, vol. 33, no. 9, Nov. 2020, Art. no. 106832.

[20] G. He, D. S. Mallapragada, A. Bose, C. F. Heuberger-Austin, and E. Gençer, "Sector coupling via hydrogen to lower the cost of energy system decarbonization," *Energy Environ. Sci.*, vol. 14, no. 9, pp. 4635–4646, 2021.

[21] H. Böhm, S. Moser, S. Puschnigg, and A. Zauner, "Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials," *Int. J. Hydrogen Energy*, vol. 46, no. 63, pp. 31938–31951, Sep. 2021.

[22] P. P. Chinaris, G. N. Psarros, E. S. Chatzistylianos, and S. A. Papathanassiou, "Impact of natural gas price variations and consumption limitation on the decarbonization of sector-coupled energy systems," *IEEE Access*, vol. 11, pp. 131573–131596, 2023.

[23] HOMER. (2021). *Hybrid Renewable and Distributed Generation System Design Software*. [Online]. Available: https://www.homerenergy.com/



ANSHUL GOYAL (Graduate Student Member, IEEE) received the B.Tech. degree in electrical engineering from Nirma University, Ahmedabad, Gujarat, India, in 2015. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He was an Executive Electrical Engineer in the EPC Business of the Oil & Gas Sector with Linde Engineering, Vadodara, Gujarat, India, from 2015 to 2019. His research interests include the integration of energy storage systems and carbon-neutral technologies into the power systems, electricity markets modeling and design, and the optimization of power systems.

KANKAR BHATTACHARYA (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Indian Institute of Technology Delhi, New Delhi, India, in 1993. He was a Faculty Member of the Indira Gandhi Institute of Development Research, Mumbai, India, from 1993 to 1998, and the Department of Electric Power Engineering, Chalmers University of Technology, Gothenburg, Sweden, from 1998 to 2002. In 2003, he joined the Electrical and Computer Engineering Department, University of Waterloo, Waterloo, ON, Canada, where he is currently a Full Professor. His current research interests include power system economics and operational aspects. He is a Registered Professional Engineer in the province of Ontario.

• • •