Performance Assessment of Prototype Residential Cogeneration Systems in Single Detached Houses in Canada

A Report of Subtask C of
FC+COGEN-SIM
The Simulation of Building-Integrated
Fuel Cell and Other Cogeneration Systems

Annex 42 of the
International Energy Agency
Energy Conservation in Buildings and Community Systems Programme
First published: December 2007

AUTHORED BY:
Hajo Ribberink (Natural Resources Canada)
Maria Mottillo (Natural Resources Canada)
Denis Bourgeois (Université Laval)

ANNEX 42 OPERATING AGENT:
Ian Beausoleil-Morrison (Natural Resources Canada)

ANNEX 42 SUBTASK C LEADER:
Viktor Dorer (Empa, Switzerland)

CITATION

Hajo Ribberink (Natural Resources Canada). Performance Assessment of Prototype Residential Cogeneration Systems in Single Detached Houses in Canada. A Report of Subtask C of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme. (161 pages).

Copies of this report may be obtained from the Annex 42 web site at: www.cogen-sim.net or from the IEA/ECBCS Bookshop at: www.ecbcs.org.

DISCLAIMER

Participating countries in ECBCS:
Australia, Belgium, CEC, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

ISBN No. 978-0-662-47618-4
Catalogue No.: M154-14/6-2008E-PDF

Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to facilitate and accelerate the introduction of energy conservation, and environmentally sustainable technologies into healthy buildings and community systems, through innovation and research in decision-making, building assemblies and systems, and commercialisation. The objectives of collaborative work within the ECBCS R&D programme are directly derived from the on-going energy and environmental challenges facing IEA countries in the area of construction, energy market and research. ECBCS addresses major challenges and takes advantage of opportunities in the following areas:

- exploitation of innovation and information technology;
- impact of energy measures on indoor health and usability;
- integration of building energy measures and tools to changes in lifestyles, work environment alternatives, and business environment.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)

Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing
Annex 39: High Performance Insulation Systems
Annex 40: Building Commissioning to Improve Energy Performance
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)
Annex 43: Testing and Validation of Building Energy Simulation Tools
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

(*) - Completed

Annex 42

The objectives of Annex 42 were to develop simulation models that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental, and economic performance of the technologies. This was accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis was placed upon fuel cell cogeneration systems and the Annex considered technologies suitable for use in new and existing single and low-rise-multi-family residential buildings. The models were developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives Annex 42 conducted research and development in the framework of the following three Subtasks:

- Subtask A : Cogeneration system characterization and characterization of occupant-driven electrical and domestic hot water usage patterns.
- Subtask B : Development, implementation, and validation of cogeneration system models.
- Subtask C : Technical, environmental, and economic assessment of selected cogeneration applications, recommendations for cogeneration application.

Annex 42 was an international joint effort conducted by 26 organizations in 10 countries:

Belgium	▪ University of Liège / Department of Electrical Engineering and Computer Science ▪ COGEN Europe ▪ Catholic University of Leuven
Canada	▪ Natural Resources Canada / CANMET Energy Technology Centre ▪ University of Victoria / Department of Mechanical Engineering ▪ National Research Council / Institute for Research in Construction ▪ Hydro-Québec / Energy Technology Laboratory (LTE)
Finland	▪ Technical Research Centre of Finland (VTT) / Building and Transport
Germany	▪ Research Institute for Energy Economy (FfE)
Italy	▪ National Agency for New Technology, Energy and the Environment (ENEA) ▪ University of Sannio ▪ Second University of Napoli
Netherlands	▪ Energy Research Centre Netherlands (ECN) / Renewable Energy in the Built Environment
Norway	▪ Norwegian Building Research Institute (NBRI) ▪ Telemark University College
United Kingdom	▪ University of Strathclyde / Energy Systems Research Unit (ESRU) ▪ Cardiff University / Welsh School of Architecture
United States of America	▪ Penn State University / Energy Institute ▪ Texas A&M University / Department of Architecture ▪ National Institute of Standards and Technology ▪ National Renewable Energy Laboratory

- National Fuel Cell Research Center of the University of California-Irvine

Switzerland

- Swiss Federal Laboratories for Materials Testing and Research (EMPA) / Building Technologies Laboratory
- Swiss Federal Institute of Technology (EPFL)/ Laboratory for Industrial Energy Systems
- Hexis AG (Hexis)
- Siemens Switzerland AG (Siemens)

CONTENTS

FIGURES

TABLES

SUMMARY

A performance assessment study has been performed on the application of *prototype* Stirling engine (SE) and Solid Oxide Fuel Cell (SOFC) residential cogeneration systems in single family detached houses in Canada. This study is part of Subtask C of the IEA/ECBCS Annex 42 "FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems".

The detailed mathematical models developed within Annex 42 (Beausoleil-Morrison and Kelly (eds). 2007) have been calibrated with measured data from prototype cogeneration devices (Beausoleil-Morrison (ed). 2007). These models have been implemented into existing whole-building simulation programs, including ESP-r, within Annex 42. The current work employs the ESP-r implementation of these models along with synthetic electricity and domestic hot water demand profiles that were produced by Annex 42 using calibrated event based generators (Knight et al. 2007). The objectives of the current work were to realistically forecast the Greenhouse gas (GHG) emission reduction and efficiency improvement of these prototype systems in comparison to a reference system consisting of a condensing furnace, a high-efficiency water heater, and on-the-margin grid electricity.

The results of this analysis show that the Greenhouse gas (GHG) emission reduction potential is mainly determined by the displaced emissions of grid electricity. Application in Ontario of the prototype SOFC system, which has a relatively high electricity production, would substantially reduce the GHG emissions of the house, despite a very low net cogeneration system efficiency (conversion of fuel to net AC power + useful heat, HHV basis) of 37%. The prototype SE system has a higher system efficiency but low power output and negligible GHG emission reduction when applied in heat load following operation in Ontario. The prototype cogeneration units in this study would cause GHG emissions to increase when applied in Québec, Alberta, and British Columbia.

SE systems operated in heat load following mode consume between 5% - 10% more natural gas than the reference system, a difference that may already be bridged by relatively easy measures like reducing heat storage losses (more and/or better insulation) and balance of plant power consumption (high-efficiency DC-motor pumps). The SOFC needs 50% - 150% additional natural gas input compared to the reference system, partly due to the necessity to dump excess heat. Improvements to both SE and SOFC prototype systems are possible that will allow the systems to reduce the primary energy input to the house and have substantial GHG emission reductions.

The current study has focused on the measured performance of *prototype* residential cogeneration systems. These prototypes

- had efficiencies well below those expected for mature technology,
- had unsophisticated operating strategies that could be vastly improved (SOFC), and
- had inappropriate electrical capacities (SE was too small, SOFC too large).

The results of this study provide a 'snapshot' of the development of residential cogeneration systems, which is certainly not representative of the *potential* of the technologies. The report

contains valuable information for designers of residential cogeneration systems in relation to the optimization of their systems, but should not be used to form an opinion on the potential impact of these technologies A further investigation into the future potential of residential cogeneration technologies in Canada is necessary and recommended.

1 INTRODUCTION

Residential cogeneration is generally believed to hold a promise of increased efficiencies, reduced greenhouse gas emissions, and reduced peak-load and grid dependence through on-site co-production of heat and power. Numerous simulation activities have been performed over the last decade to quantify the advantages of the application of cogeneration systems based upon an Internal Combustion Engine (ICE), a Stirling engine (SE), an Organic Rankine Cycle (ORC), a Polymer Electrolyte Membrane Fuel Cell (PEMFC), or a Solid Oxide Fuel Cell (SOFC) in houses. A literature review by Dorer (2007) summarizes a total of over 100 publications. Many of these have been based upon a simplified performance-map approach that decouples the performance of the cogeneration unit from that of the rest of the building. However, until recently a comparison of the outcome of these simulation studies to the test results of the actual application of the cogeneration units in real houses has not been possible due to the early stage of development of most residential cogeneration technologies and/or the limited availability of prototype units.

1.1 Results from early field trials in the UK

In the UK a field trial of prototypes of residential cogeneration systems was initiated in 2003 by the Carbon Trust. Prototype residential cogeneration systems were installed in representative homes in the UK gradually through 2004 and 2005 and an interim report on the preliminary results of the field trial was published at the end of 2005 (Carbon Trust, 2005). The conclusion on these very early findings was that the "performance is not as encouraging as had been hoped based on published, modelled performance of the technology at the outset of the trial". The interim report states as reasons for the disappointing results:

- The actual, real-world efficiencies of the units are lower than assumed by existing modelling exercises.
- The amount of electricity generated is much lower than forecasted.
- Electricity exported out of the building is considerably higher than expected.

The lower efficiency and lower amount of electricity production were concluded to be related to the design and operation of the prototype units. The intermittent heat demand of the house did not interact well with the operational behaviour of the units, which is characterized by relatively long warm-up periods due to the high thermal mass of the units. During this warm-up phase no electricity is produced, and a lot of heat is absorbed in the units to bring them to their operating temperatures. Most of this heat cannot be usefully recovered. In a separate field study, Entchev et al. (2004) noted many of the same performance characteristics with a SE cogeneration system. These effects are not captured with decoupled performance-map models.

The mismatch in electricity export appears to be related to a common modelling assumption that the typical electricity demand in homes during a half-hour is similar to the average demand in that half-hour. The field trial data clearly show that this is incorrect. The domestic electricity consumption profile is much better characterised by a baseload of 100-500 W with short very high peaks (up to 10 kW) superimposed on this baseload. This baseload power consumption is generally (much) lower than the power production by the cogeneration unit, resulting in considerable export of excess power. Hawkes and Leach (2005) have demonstrated that the use of such coarse temporal precision in modelling can lead to significant errors.

It seems that some of the modelling studies used to forecast the performance of the prototypes in the Carbon Trust field trial overestimated the performance of the residential cogeneration and its carbon reduction due to the use of oversimplified assumptions on the operation of the cogeneration unit as well as on the energy demand pattern of the house it was placed in.

1.2 Objectives of current study

The current study sets out to realistically forecast the efficiency improvement and carbon emission reduction of prototype Stirling Engine (SE) and Solid Oxide Fuel Cell (SOFC) residential cogeneration systems applied in single detached houses in Canada. The study does this by using:

- Detailed mathematical models to simulate the performance of the prototype cogeneration devices (Beausoleil-Morrison and Kelly (eds). 2007, Beausoleil-Morrison et al. 2006a). These are system-level models that consider the thermodynamic performance of all components that consume energy and produce electrical and thermal output. These models are integrated with those of associated HVAC components, controls, and the building.
- Component models for SE and SOFC residential cogeneration systems that were calibrated using detailed measured performance data of prototype SE and SOFC cogeneration devices (Beausoleil-Morrison (ed), 2007).
- A house model that is based upon the Test House of the Canadian Centre for Housing Technology (CCHT), which was previously modeled and validated thoroughly (Purdy and Beausoleil-Morrision, 2001).
- Realistic electric and domestic hot water (DHW) load profiles generated by event based profile generators that used measured data for defining the characteristic draws of electricity and DHW (Knight et al. 2007).
- On the margin displaced greenhouse gas (GHG) emissions of central power production.
- The well-validated ESP-r whole building simulation program (Clarke, 2001) run with small time steps (100 seconds).

1.3 Annex 42 and Performance Assessment Methodology

The study presented in this report is part of Subtask C of Annex 42 “The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC + COGEN-SIM)” of the International Energy Agency (IEA) implementing agreement on Energy Conservation in Buildings and Community Systems program (ECBCS). It is one of five studies performed in subtask C into the performance of residential cogeneration systems applied in houses and/or apartment buildings in different countries in the world (Canada, Germany, Italy, and Switzerland). The reports of these studies will become available for downloading from the ECBCS website (www.ecbcs.org) at the end of 2007.

All five studies are based upon a common Performance Assessment Methodology (PAM). This methodology was developed within Annex 42 and is described by Dorer and Weber (2007). It has been the intent of the author to describe the current study in a report that can be understood without prior knowledge of the Annex 42 performance assessment methodology. However, the interested reader is referred to the PAM report (Dorer and Weber, 2007) for more detailed information.

Parts of the results of the current study have previously been published in (Ribberink et al. 2007).

2 SIMULATION MODELS AND INPUTS

The performance of residential cogeneration systems depends strongly on country-specific and local conditions. The heat load of the house varies with building practices and climate, while occupant behaviour determines electricity and DHW loads. The efficiency improvements and reduction of GHG emissions due to the application of residential cogeneration depend on the power production structure and the chosen reference technologies. This means that the outlook for the application of residential cogeneration may vary significantly between (parts of) countries and conclusions from application studies may not be valid for other regions or countries.

2.1 The Canadian setting

Most houses in Canada have a wood based structure resulting in houses with a low thermal mass. Almost 60% of houses in Canada are single detached houses with an average floor area of 141 m^2 (OEE, 2007). This house type is used in this study.

Canada is a very large country with in general a continental climate, characterized by both a cold winter and a hot summer. Regional differences on the performance of the residential cogeneration are investigated by performing simulations for a number of locations across Canada.

Canada's extensive natural gas grid reaches form Québec City in the east to Vancouver in the west. Most major metropolitan areas are serviced by natural gas, making this the fuel of choice for the residential cogeneration systems.

Most houses in Canada are heated by a forced air furnace, where heated air is transported to various rooms in the house through a ductwork system. A state of the art condensing furnace with an Annual Fuel Utilization Efficiency of 96.3% (based upon the higher heating value, HHV) is taken for the reference technology (Gamanet, 2007).

Domestic hot water is predominantly heated in storage vessels by natural gas or electricity. Water heating efficiencies of 85% (HHV) are obtained for natural gas fired water heaters operating continuously (Gamanet, 2007). However, normal intermittent operation will result in a maximum annual average efficiency of only 62% (HHV) due to stand still losses. A simple one node water tank model with an annual 62% efficiency (HHV) is used in the simulations. A built-in natural gas burner serves as a back-up burner for preparing DHW.

The average Canadian household consumes approximately 6600 kWh of non-HVAC electricity (OEE, 2007). HVAC electricity is the power consumed by Heating, Ventilation, and Air Conditioning equipment. The average daily DHW consumption is around 230 L/day. Event based profile generators are used to make load profiles that match the demands of the average household living in a one family single detached house.

In Canada the power production has historically been a provincial responsibility. Major differences in geographical conditions have resulted in a large variation in the provincial power production mix, ranging from a (vast) majority of hydropower in Québec and British Columbia to an almost exclusive use of coal in Alberta and Saskatchewan. The application of residential cogeneration systems at various locations in Canada was investigated to identify the differences in displaced GHG emissions for various provinces.

2.2 Stirling engine model

In 2003 a Stirling engine based Combined Heat and Power (CHP) unit was tested in the CCHT test house, located in Ottawa (Bell et al. 2003). The unit was used to heat water for space heating and DHW. The unit was run to operate in a heat load following mode keeping the water temperatures in storage vessels within a certain band. The engine was controlled to always perform complete operating cycles (warm-up, normal operation, shutdown, and inoperation) and was not allowed to restart before the full shutdown phase had ended. Normal operation in these cycles equalled operation at full load (700 W electric and around 6 kW heat output).

The data gathered during this testing was used to calibrate the model (i.e. establish its inputs) of Beausoleil-Morrison, I. and Kelly, N. (eds) (2007). This calibration procedure is documented in Beausoleil-Morrison (2007). Simulations with the SE model have been performed for both a heat load following operating mode and an electricity load following mode.

2.3 Solid Oxide Fuel Cell model

A series of experiments were conducted with a prototype SOFC cogeneration system. These data were used to calibrate the model of Beausoleil-Morrison et al. (2006a). The calibration procedure is described in Beausoleil-Morrison et al. (2006b).

The test program included the characterization of the electrical and thermal output at varying loads, cooling water temperatures and flows. Unfortunately, the start-up and cool down behaviour of the SOFC unit could not be calibrated due to a lack of data.

The SOFC residential cogeneration system has a nominal (and maximum) net electrical output of 2.7 kW and a thermal output of around 3 kW. Although the SOFC prototype system has part load capabilities, the efficiency of the unit would decrease dramatically at part loads below 85%, as a supplementary heater needs to be operated to keep the SOFC stack at its desired temperature. For the simulations it was decided to operate the unit continuously at its nominal operating conditions. However, a three-month summer stop has been introduced, as no significant heat demand was foreseen during this period matching the magnitude of SOFC heat production.

2.4 SE and SOFC systems

The system layout of the Stirling engine and SOFC residential cogeneration systems is very similar. The cooling water of the cogeneration unit is used to heat water in a storage vessel. This storage vessel provides DHW and warm water for the fan-coil unit that heats the house. The storage tank has a backup burner. A schematic overview of the SE and SOFC cogeneration systems is given in Figure 2.1. Figure 2.2 presents an artist impression of a residential cogeneration system and its energy streams.

When the simulated SE system is controlled in a heat load following mode, the SE is started when the temperature of the water in the storage vessel drops below 60 °C. The engine will operate until its outgoing cooling water will reach a temperature of 80 °C. The corresponding temperature of the storage vessel will then be around 73 °C for the pump flow rate used in this study. The back-up burner will be activated when the tank temperature falls below 50 °C.

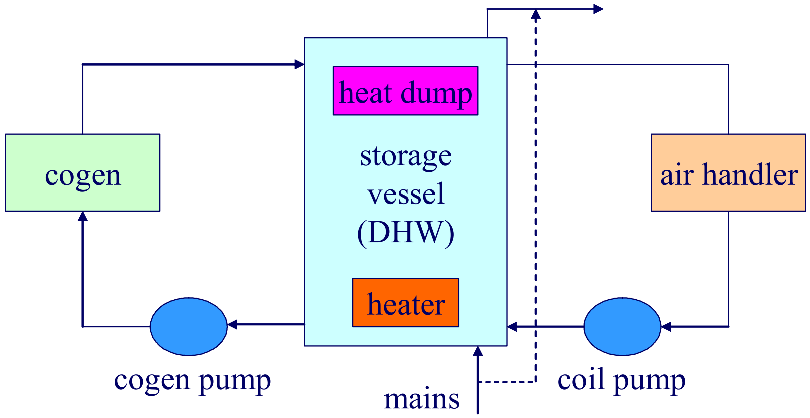


Figure 2.1 Schematic overview of the SE and SOFC residential cogeneration systems

In the electricity load following mode, the SE will in principle be run whenever there is a demand for electricity. The SE will be operated at a load between 50 and 100% of full load, depending on the specific electricity demand. If the electric load is smaller than the minimum SE power production, excess electricity will be exported to the grid. For electric loads exceeding the maximum power production of the SE unit the remainder will be met by import from the grid. Only when the cooling water outlet temperature of the SE unit surpasses the 80 °C limit, the unit will be shut off or the unit will not be allowed to start. As in the heat load following mode, the back-up burner of the water storage tank will be fired in case the tank temperature drops below 50 °C.

The SOFC system will be run in continuous operation all year except for the period June through August. The SOFC unit will then be inoperative and all heat loads will be supplied by the back-up burner in the hot water tank. When the SOFC heat supply will cause the water tank temperature to reach 92 °C, heat is dumped from the tank until the storage temperature has dropped to 90 °C. In the current study a rather fictitious heat dump facility is used that simply removes the appropriate amount of energy from the energy balance of the water tank model. The heat dump facility is foreseen to be upgraded to an external cooling loop with pump and fan coil unit in the near future. This upgrade would also allow the electricity consumption of pump and fan to be included in the simulations.

The balance of plant equipment of both cogeneration systems is assumed to be standard equipment. The power consumption of the cogeneration cooling loop pump is 80 W. The heating coil loop pump draws 100W, while the heating coil fan uses 200 W electric.

The thermostat set points for space heating are 21 °C from 8 to 24 hr and 18 °C from 0 to 8 hr.

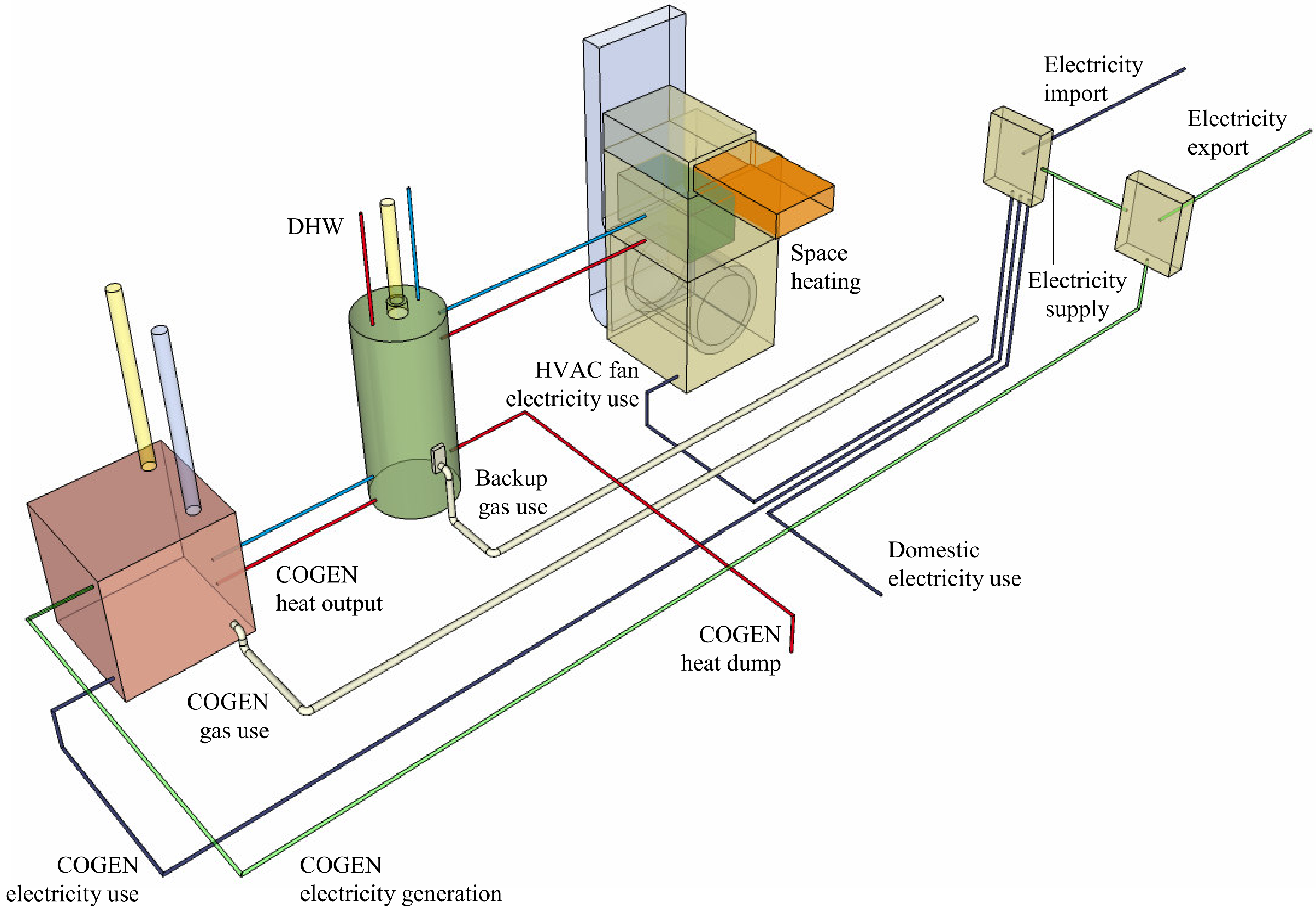


Figure 2.2 Artist impression of a residential cogeneration system and its energy streams. (the location of the connections to and from the storage tank are indicative and do not necessarily reflect the height at which they would be located in reality)

2.5 House models

Four house models have been used in this study. All models are based upon the CCHT test house (CCHT, 2007). This house was built conform the R2000 standard for energy efficient building and has a floor area of 210 m^2. This house ('ccht') is representative of new single detached housed built in Canada. The resulting space heating demand of this house is 39.7 GJ (i.e. after casual gains have been taken into account and using weather data for Ottawa for 2004).

The 'ccht141' house model combines the building characteristics of the CCHT house with the floor area of the average Canadian single detached house (141 m^2). The ccht141 house is the base case model for this study and requires 27.8 GJ to be provided by the space heating equipment.

Two variants of the ccht141 model were made by adjusting the insulation level and the air tightness of the house. The 'ccht141_avg' house has a heat load equal to that of the average existing single detached house in Canada (71.3 GJ). Demonstrated aspects of an even more energy efficient way of building have been implemented in the 'ccht141_future' model, which has a very small resulting heat load (8.2 GJ).

2.6 Demand profiles for electricity and DHW

Realistic high resolution (5 minute time step) synthetic electric and DHW profiles have been produced using event based profile generators developed by the National Research Council of Canada (NRC) and Annex 26 of the IEA Solar Heating and Cooling Program.

Both generators have been calibrated using measured data from characteristic draws. More details on the NRC generator for electricity profiles can be found in Knight et al. (2007). For the Annex 26 DHW profile generator the reader is referred to Jordan and Vajen (2001).

2.7 Casual gains

Most electricity used by a household ends up as heat in the house. In the simulations 80% of the electric load is added as heat (casual gain) to the house. The remainder represents the external lighting and e.g. the hot exhaust of an electrically heated clothes dryer.

All space heating and DHW supply equipment is assumed to be located in a part of the house that does not belong to the heated zones. Heat losses from furnace, SE, and SOFC system (including hot water storage tank) are not taken as a source of casual gain in the house.

The occupants of the house were assumed to provide 200 W of heat continuously.

3 PERFORMANCE METRICS

The performance of the SE and SOFC residential cogeneration systems is first expressed in the GHG emission reduction they achieve in comparison to the reference situation of separate heat and power production using best available heating technology (condensing hot air furnace and high efficient water heater) and central power production. Secondly, the efficiencies of the cogeneration systems in producing heat and power, and in providing the requested energy services to the house are investigated.

3.1 Greenhouse gas emissions

The reduction of GHG emissions has been calculated taking into account the displaced emissions of central power production plants on a temporal basis. Two methods have been applied:

1. The first method uses a correlation between the publicly available Hourly Ontario Electricity Price (HOEP) and the on-the-margin fuel source(s) for central power production in Ontario that would be displaced by cogeneration power production. This method was developed at Natural Resources Canada and is described in (Mottillo et al. 2006). The majority of cases have been simulated using climate data for Ottawa for 2004 and the corresponding displaced emission data from the 'HOEP' method.
2. A second method is used in the comparison of the simulation results for different locations across Canada (Montréal, Ottawa, Calgary, and Vancouver). The PERRL study (ICF Consulting 2003) presents monthly data on displaced emissions per province. Climate data for the standard 'cwec' reference year (Numerical Logics, 1999) have been used for all locations in this comparison.

Upstream fuel cycle emissions (i.e. the emissions for getting the primary energy from its source to the house or power plant) are taken into account in the GHG emissions reduction calculations.

3.2 Efficiencies

Efficiencies are defined on three levels:

- the cogeneration unit (CGU),
- the cogeneration system (CGS), and
- the house.

3.2.1 Cogeneration unit efficiency

The efficiencies for the cogeneration unit present the efficiency of the conversion of natural gas into electricity and heat. The net cogeneration efficiency ($\eta_{HHV,CGU,net}$) is defined as:

$$\eta_{HHV,CGU,net} = \frac{OE_{El-GCU,net} + OE_{Th-CGU,gross} - OE_{Th-HS,dump}}{DE_{Fuel-CGU}} \quad (1)$$

in which $OE_{El\text{-}CGU,net}$ is the net AC power output of the cogeneration unit, $OE_{Th\text{-}CGU,gross}$ the gross heat output of the cogeneration unit, $OE_{Th\text{-}HS,dump}$ the heat dumped from the heat storage tank, and $DE_{Fuel\text{-}CGU}$ the energy content (HHV) of the fuel consumed by the cogeneration unit.

Similarly, the net electric cogeneration efficiency ($\eta_{HHV,El\text{-}CGU,net}$), the gross thermal cogeneration efficiency ($\eta_{HHV,Th\text{-}CGU,gross}$), and the net thermal cogeneration efficiency ($\eta_{HHV,Th\text{-}CGU,net}$) are defined:

$$\eta_{HHV,El-CGU,net} = \frac{OE_{El-CGU,net}}{DE_{Fuel-CGU}} \tag{2}$$

$$\eta_{HHV,Th-CGU,gross} = \frac{OE_{Th-CGU,gross}}{DE_{Fuel-CGU}} \tag{3}$$

$$\eta_{HHV,Th-CGU,net} = \frac{OE_{Th-CGU,gross} - OE_{Th-HS,dump}}{DE_{Fuel-CGU}} \tag{4}$$

3.2.2 Cogeneration system efficiency

The efficiencies of the cogeneration system (cogeneration unit plus balance of plant (BOP) equipment) will differ from those of the cogeneration unit alone. Heat losses from the storage tank and power consumed by the system's pumps will reduce the efficiency. The use of the back-up burner will also influence the efficiency.

The net cogeneration system efficiency ($\eta_{HHV,CGS,net}$) is defined as

$$\eta_{HHV,CGS,net} = \frac{OE_{El-CGU,net} + NE_{SH} + NE_{DHW} - NE_{El-BOP}}{DE_{Fuel-CGU} + DE_{Fuel-BB}} \tag{5}$$

with NE_{SH} and NE_{DHW} being the thermal energy supplied to meet the space heating demand of the house (after casual gains have been accounted for) and the domestic hot water demand, respectively. $NE_{El\text{-}BOP}$ is the electricity draw of the balance of plant equipment. Only the power for the two pumps (see Figure 2.1) is taken into account, since the fan of the air handler unit would have to be present in a furnace anyway. $DE_{Fuel\text{-}BB}$ is the energy content (HHV) of the fuel consumed by the back-up burner in the storage tank.

The net system electric efficiency ($\eta_{HHV,El\text{-}CGS,net}$) and net system heat efficiencies ($\eta_{HHV,Th\text{-}CGS,net}$) are defined similarly:

$$\eta_{HHV,El-CGS,net} = \frac{OE_{El-CGU,net} - NE_{El-BOP}}{DE_{Fuel-CGU} + DE_{Fuel-BB}} \tag{6}$$

$$\eta_{HHV,Th-CGS,net} = \frac{NE_{SH} + NE_{DHW}}{DE_{Fuel-CGU} + DE_{Fuel-BB}} \tag{7}$$

3.2.3 House efficiency

The net house efficiency ($\eta_{HHV,house,net-coal}$, $\eta_{HHV,house,net-nat.gas}$) is the overall efficiency of meeting the demand for (non-HVAC) electricity, space heating, and DHW of the house. The 'coal' or 'nat.gas' at the end of the parameter name refers to whether grid electricity is assumed to come from a coal fired power plant or from a natural gas fired combined cycle power plant. In general,

$$\eta_{HHV,house,net} = \frac{NE_{El-non-HVAC} + NE_{SH} + NE_{DHW}}{DE_{Fuel-CGU} + DE_{Fuel-BB} + PE_{El-grid}} \quad (8)$$

in which $NE_{El-non-HVAC}$ is the non-HVAC electricity demand of the house, $PE_{El-grid}$ is the required primary energy (natural gas or coal) input to the central power plant for supplying the amount of electricity imported by the house. $PE_{El-grid}$ is negative for a net export of electricity to the grid.

Central power production is rated at 51% (HHV) for a natural gas fired combine cycle, and at 32% (HHV) for coal based power production. A 92% distribution efficiency is taken into account for grid electricity, reducing the efficiencies for 'net delivered' electricity to the house to 46.9% (HHV) and 29.4% (HHV) for power production from natural gas and coal, respectively. All efficiencies are based upon the energy content of the fuel delivered to the house and the primary energy inputs to the power plants. No further upstream efficiency losses are considered for the exploration, extraction, processing, or transport of the fuels to the power plant.

For reference cases, similar efficiencies can be defined by replacing the fuel input of the cogeneration unit by the fuel input of the furnace in equation 5-8.

4 SIMULATION RESULTS AND DISCUSSION

4.1 SE and SOFC base cases

In *heat load following operation*, the SE system is operated in a cyclic mode. At full load, $\eta_{HHV,El\text{-}CGU,net}$ is 8.4%, $\eta_{HHV,Th\text{-}CGU,net}$ is 74.4%, totalling 82.8% for $\eta_{HHV,CGU,net}$. However, start-stop losses decrease this number to an annual average net cogeneration efficiency of 78.9% (7.0% electric and 71.9% heat). The pumps of the SE system absorb approximately 20% of the SE power production. Heat losses from the storage tank cause the $\eta_{HHV,Th\text{-}CGS,net}$ to drop to 60.8%. The resulting $\eta_{HHV,CGS,net}$ is 66.2%, substantially lower than the equivalent full load efficiency.

The results for the base case SE system in *electric load following operation* show the same trends as those for the heat led SE system, though at reduced efficiencies. The $\eta_{HHV,El\text{-}CGU,net}$ is 5.9%, $\eta_{HHV,Th\text{-}CGU,net}$ is 68.0%, and $\eta_{HHV,CGU,net}$ is 73.9%, a full 5%-points lower than for the heat load following operating mode. The lower performance is related to the fact that the SE system has more operating hours in electric load following mode. However, a substantial part these hours the unit runs at part load where both the electric and thermal efficiency are lower than at full load. Besides, due to the extended number of operating hours, the parasitic electricity consumption of the pumps of the SE system has increased to almost half of the SE system's power production! And also the heat losses from the storage tank are higher due to a higher average temperature of the water storage in comparison to the heat load following case. The $\eta_{HHV,CGS,net}$ for the electric load following case is 58.5%, almost 8%-points lower than for the heat led case.

The SOFC residential cogeneration system is run continuously at full load, with a $\eta_{HHV,El\text{-}CGU,net}$ of 23.6% and a $\eta_{HHV,Th\text{-}CGU,gross}$ of 25.4%. However, 38.3% of the heat output of the SOFC can not be used and needs to be dumped, decreasing $\eta_{HHV,Th\text{-}CGU,net}$ to 15.6% and $\eta_{HHV,CGU,net}$ to 39.3%.

The net house efficiencies for the SE system run in heat load following mode are only a little lower than those for the reference case. For the electricity load following SE system and the SOFC system, the difference is bigger.

Table 4.1 presents the efficiencies for the SE and SOFC base case systems and (where appropriate) for the reference case. Detailed overviews of the simulation results for these three cases and for all other cases are presented in the appendix. The names of all simulation cases follow the general format: XX_YYY_Z, with:

- XX: the cogeneration technology (SE for Stirling systems, SOFC for SOFC systems)
- YYY: the case number (given in the results tables)
- Z: the operating mode for SE cases (E for electric load following, H for heat load following)

Example: The case number for all base cases is 100. So, the name for the base case heat led SE system is SE_100_H, SE_100_E is the name of the SE system in electric load following mode, and the base case SOFC system is named SOFC_100.

Table 4.1 Energy efficiencies of base case SE and SOFC residential cogeneration systems, and of the reference case.

	Reference base case (%)	SE base case (heat load following) (%)	SE base case (electric load following) (%)	SOFC base case (%)
$\eta_{HHV,El-CGU,net}$		7.0	5.9	23.6
$\eta_{HHV,Th-CGU,gross}$		71.9	68.0	25.4
$\eta_{HHV,Th-CGU,net}$		71.9	68.0	15.6
$\eta_{HHV,CGU,net}$		**78.9**	**73.9**	**39.3**
$\eta_{HHV,El-CGS,net}$		5.4	2.8	22.3
$\eta_{HHV,Th-CGS,net}$		60.8	55.7	14.8
$\eta_{HHV,CGS,net}$	**(80.4)**	**66.2**	**58.5**	**37.1**
$\eta_{HHV,house,net-coal}$	46.5	45.3	42.2	42.0
$\eta_{HHV,house,net-nat.gas}$	61.7	57.3	53.2	33.6
Case number	100	100	100	100

4.2 Emission reduction for locations across Canada

The fuel source for central power production that is displaced by the cogeneration system's electricity production heavily influences the potential for GHG emission reduction. The second column of Table 4.2 presents the annually averaged emission factors of the displaced fuel sources using data from the PERRL study (ICF Consultancy 2003) in case all the non-HVAC power of the house would be supplied by the cogeneration unit for different locations across Canada. A similar emission factor $GHG_{CGS,f}$ can be defined for the cogeneration cases

$$GHG_{CGS,f} = \frac{GHG_{CGS,total} - GHG_{ref,SH+DHW}}{OE_{El-CGU,net} - NE_{El-BOP,extra}} \qquad (9)$$

in which $GHG_{CGS,total}$ is the total GHG emission due to the natural gas consumption of the cogeneration system, $GHG_{ref,SH+DHW}$ the combined GHG emission of the furnace and the water tank for the reference case, and $NE_{El-BOP,extra}$ the additional electricity consumption for BOP equipment of the cogeneration system over that for the reference system. The nominator in Equation 9 represents the GHG emissions attributed to the electricity production, while the denominator equals the reduction of electricity import from the grid in comparison to the reference case. The application of residential cogeneration systems will reduce the GHG emissions if the emission factor of the cogeneration system ($GHG_{CGS,f}$) is lower than that for the central power production it displaces, and vice versa. The emission factors for the SE and the SOFC system are also given in Table 4.2.

Table 4.2 Annual average GHG emission factors for on-the-margin central power production, and for SE and SOFC residential cogeneration systems.

	GHG emission factor (kg CO_2e/kWh)			
Location (case number)	Central power production ('on-the-margin')	$GHG_{CGS,f}$ SE system (heat load follow.)	$GHG_{CGS,f}$ SE system (elec. load follow.)	$GHG_{CGS,f}$ SOFC system
Montréal (810)	0.186	0.951	1.943	0.746
Ottawa (820)	1.067	0.957	1.998	0.749
Calgary (830)	0.480	0.941	1.995	0.751
Vancouver (840)	0.379	1.038	5.772	0.802

Table 4.2 clearly shows that the potential for emission reduction is mainly determined by the (mix of) specific central power production technology (hydro, natural gas, coal) locally used. The very low net power production of the SE systems in electric load following mode is the reason for the high emission factors for these cases. The detailed overviews of the results for these cases can again be found in the appendix.

4.3 Emission reduction using the HOEP method

The HOEP method provides temporal information on the on-the-margin fuel source(s) in Ontario. For the reference case, the annual average emission factor for displaced grid electricity is 0.850 kg CO_2e/kWh. This indicates that the cogeneration power production would primarily displace emissions from a coal-fired power plant (1.076 kg CO_2e/kWh) and to a lesser extent power production based on natural gas (0.461 kg CO_2e/kWh) and hydro (0.0178 kg CO_2e/kWh).

A number of variations on the base cases have been simulated for the SE and SOFC systems (and for the corresponding reference cases) to investigate the relative importance of the demand for electricity, space heating, or DHW, and the temperature and size of the storage tank on the performance of the cogeneration systems. Table 4.3 presents the variation in input parameters for the different cases and the main results per case. Each case was defined by changing only one parameter in comparison to the base case.

The results of the parameter variation cases displayed in Table 4.3 show that of the parameter variations the size of the storage vessel has the biggest impact on the performance and emission reduction potential of both SE and SOFC systems. The increase in heat losses for larger storage tanks influences the performance of the system much stronger than the other varied parameters. It is clear that residential cogeneration systems need water storage tanks that are (much) better insulated than current water heaters. Even for the base case SE systems, the heat loss of the storage tank accounts to around 10% of the overall efficiency (see Table 4.1).

For *heat led* SE residential cogeneration systems, the variation of the other parameters has little impact on the house emissions. Using HOEP and climate data for 2004, GHG emission reductions would range from +1% for the ccht141_avg house (high space heating load) to -2% for the ccht141_future house (very low space heating load).

Table 4.3 Main results for SE and SOFC simulation cases (HOEP method, Ottawa, 2004)

Variation of	Case no.	Param. values	Em. reduction (%)	Prim. en. reduction (%)	$\eta_{HHV,\ El\text{-}CGS,net}$ (%)	$\eta_{HHV,\ Th\text{-}CGS,net}$ (%)	$\eta_{HHV,\ CGS,net}$ (%)	Heat dumped (%)	$GHG_{CGS,f}$ (kg CO_2e/ kWh)
SE_H cases	**100**		**-1.4**	**-7.7**	**5.4**	**60.8**	**66.2**	**0.0**	**0.950**
Storage size [1] (kg)	210	100	-1.2	-6.4	4.7	63.5	68.1	0.0	0.945
	220	400	-4.3	-13.7	6.0	53.8	59.9	0.0	1.152
	230	2 000	-9.9	-24.3	6.7	44.8	51.6	0.0	1.385
Storage temp. [2] (°C)	310	50 – 63	-0.8	-5.8	4.9	64.2	69.1	0.0	0.900
	320	55 – 73	-1.0	-6.9	5.4	61.9	67.3	0.0	0.907
Elec. demand [3] (kWh/y)	410	4 837	-1.7	-10.1	5.5	62.0	67.5	0.0	0.929
	420	13 044	-1.0	-5.5	5.2	59.2	64.5	0.0	0.980
Space heating demand [4] (GJ/y)	510	8.2	-1.6	-6.3	4.7	53.8	58.5	0.0	1.088
	530	39.7	-0.7	-7.4	5.6	64.2	69.8	0.0	0.869
	520	71.3	1.0	-6.6	5.6	69.6	75.1	0.0	0.778
DHW demand [5] (GJ/y)	610	9.5	-1.9	-8.1	5.3	59.5	64.8	0.0	1.008
	620	21.2	-0.9	-7.3	5.4	62.6	68.0	0.0	0.895
SE_E cases	**100**		**-8.9**	**-16.1**	**2.8**	**55.7**	**58.5**	**0.0**	**2.151**
Storage size [1] (kg)	210	100	-6.7	-12.8	2.9	58.8	61.7	0.0	1.861
	220	400	-12.8	-23.7	3.7	48.6	52.3	0.0	2.167
	230	2 000	-19.4	-37.0	5.0	39.4	44.5	0.0	2.094
Storage temp. [2] (°C)	310	50 – 63	-7.2	-13.5	2.9	58.2	61.1	0.0	1.958
	320	55 – 73	-8.9	-16.1	2.8	55.7	58.5	0.0	2.151
Elec. demand [3] (kWh/y)	410	4 837	-10.2	-18.7	3.4	57.9	61.4	0.0	1.737
	420	13 044	-7.4	-13.0	1.8	53.1	55.0	0.0	3.311
Space heating Demand [4] (GJ/y)	510	8.2	-12.8	-19.4	-0.4	45.4	45.0	0.0	N/A
	530	39.7	-7.1	-14.4	3.6	60.0	63.6	0.0	1.591
	520	71.3	-4.1	-11.4	4.1	67.2	71.3	0.0	1.176
DHW demand [5] (GJ/y)	610	9.5	-9.9	-17.3	2.5	53.6	56.1	0.0	2.562
	620	21.2	-7.4	-14.4	3.3	58.2	61.5	0.0	1.730
SOFC cases	**100**		**14.3**	**-83.4**	**22.3**	**14.8**	**37.1**	**38.3**	**0.757**
Storage size [1] (kg)	220	400	13.1	-85.2	22.1	14.7	36.9	29.5	0.763
	230	2 000	10.7	-88.6	21.8	14.5	36.4	15.9	0.776
	240	25 000	-32.9	-152.7	17.4	11.6	29.0	0.0	1.018
Storage temp. [2] (°C)	310	50 – 70	13.5	-84.4	22.2	14.8	37.0	46.3	0.760
	320	50 – 80	14.0	-83.7	22.3	14.8	37.1	42.2	0.758
Elec. demand [3] (kWh/y)	410	4 837	21.8	-96.9	22.1	16.6	38.7	33.8	0.741
	420	1 3044	8.3	-69.4	22.4	12.7	35.1	44.6	0.778
Space heating demand [4] (GJ/y)	510	8.2	5.0	-120.2	22.6	8.0	30.6	60.4	0.827
	530	39.7	15.8	-71.4	21.7	18.6	40.3	32.9	0.731
	520	71.3	16.3	-51.8	19.9	27.1	47.0	23.2	0.685
DHW demand [5] (GJ/y)	610	9.5	12.5	-91.0	22.4	13.2	35.7	42.2	0.771
	620	21.2	16.1	-74.4	22.0	17.1	39.1	33.5	0.740

[1] Storage size base cases: 200 kg
[2] Storage temperature reference case: 50-60 °C;
SE base cases: 60-73°C; SOFC base case: 50-90 °C
[3] Base case electricity demand: 8 160 kWh/y
[4] Base case space heating demand: 27.8 GJ/y
[5] Base case DHW demand: 14.4 GJ/y

The house emissions for the SE systems in *electric load following mode* show a larger difference for the other parameter variation cases. The variation in space heating load has a considerable impact on the operation of the SE system. The system runs more at full load for the house with the higher heating load, and therefore operates at a higher efficiency for that case. For the house with the smallest heat load, the Stirling engine does not even produce sufficient electricity to cover the power consumption of its pumps! The impact of the other parameter variations is rather small, though bigger than for the heat led SE systems. In average, the SE_E cases increase emissions by around 7% compared to the SE_H cases.

Almost all SOFC cases show an actual reduction in GHG emissions compared to the reference case of 5 – 22%. Next to the storage size, variation of the space heating load and the electricity demand of the house result in the largest variation in GHG emission reduction. The emission reduction of the SOFC systems is primarily caused by the large amount of electricity it produces from natural gas, which mainly displaces electricity form coal fired power plants.

4.4 Reduction of primary energy use

The application of the SE and SOFC cogeneration systems has also been assessed in light of their potential to reduce the amount of primary energy (natural gas) needed for the energy demands of the house (see column “Prim. en. reduction” in Table 4.3). In this assessment, grid electricity has been assumed to be produced by a natural gas fired combined cycle power plant.

The variation of the size of the storage tank has also the biggest impact on the energy consumption of the SE systems. The results for the other SE cases vary less relative to each other, partly due to the low amount of electricity produced. All SE systems perform less than the reference systems. The heat led SE systems consume between 5% and 10% more natural gas, while the SE systems run in electric load following mode need 10 – 20% more natural gas than the reference cases (cases with variation of heat storage tank size not included).

The gap in performance between the heat led SE systems and the reference cases could likely be bridged by improvements to the BOP plant of the system (i.e. improved insulation of the storage tank and the use of high-efficient pumps). However, the performance of the SE unit itself needs to be improved considerably (e.g. by making the unit’s heat exchanger condensing), before the system can significantly outperform the reference system of condensing furnace and high efficient hot water heater.

The continuous full load operating strategy has a major influence on the performance of the SOFC residential cogeneration system. For the base case the electricity production is roughly two times the power consumption of the house. All SOFC cases show a (large) net power export to the grid. For all cases there is also more heat produced than can be used. Despite the summer stop, still up to 60% of the heat output of the SOFC has to be dumped. This heat represents up to 15% of the cogeneration unit’s energy input. The performance of the SOFC system is therefore better for cases that have a higher demand for space heating or DHW, because less heat needs to be dumped. Even a lower storage temperature does not increase the efficiency, because the benefit of lower heat losses from the storage tank is completely annulled by a higher heat dump due to the smaller heat storage capacity.

Due to the very low system efficiency, the SOFC cases require a 50% to 150% higher natural gas input than the reference cases. Major improvements to the SOFC prototype are required before the system will be able to reduce natural gas consumption compared to the reference system.

5 SENSITIVITY ANALYSIS ON THE USE OF GENERATED PROFILES VERSUS MEASURED PROFILES

The results of the performance assessment study presented in chapter 4 are based upon the use of *synthetic* electricity demand profiles. These profiles were produced by a profile generator that was calibrated using the measured electricity consumption of the major appliances. A set of *measured* electricity consumption profiles available from Hydro Quebec allowed the comparison of the simulation results for generated electricity demand profiles to those using measured profiles. However, because these new simulations were conducted using an improved version of ESP-r, first a check was performed to see what the influence of this change in ESP-r was on the simulation results.

5.1 Differences in base case results due to improvements to ESP-r

The development of the whole-building simulation program ESP-r started around 30 years ago. Since then, ESP-r has been continuously expanded and improved. In the spring of 2007, a method for calculating ground temperatures based upon climate data was implemented to replace a less accurate method that used standard profiles for the ground temperatures.

The ground temperature is used by the domestic hot water heater model to calculate the make-up water temperatures. The new method for calculating ground temperatures resulted in lower make-up water temperatures throughout the year. This means that using this new method, more fuel is needed to heat the water to the required supply temperature, compared to the previous less accurate method.

All residential cogeneration simulation cases investigated in this study have a domestic hot water heater in their system. The simulation results presented in the previous chapter were obtained using an ESP-r version that did not yet have the improved method for calculating ground temperatures. Due to technical reasons, additional simulation cases would have to be run with the newer ESP-r version. Therefore, the model for the base case Stirling engine residential cogeneration system (SE_100_H) was rerun to investigate the influence on the simulation results of this improvement to ESP-r. The results of this new run can be found in the appendix as case SE_100_H_G3.

The difference between the results of the old and the new case were limited. The lower make-up water temperatures made the fuel input of the water heater increase by 6%. The overall energy input to the house increased by around 2%, while the increase in overall GHG emissions was less than 1%. More importantly, the differences in comparing the SE case to the reference case were very small. The GHG emissions of the Stirling engine residential cogeneration system were 1.3% higher than those of the reference system. This is almost the same as the 1.4% higher emissions for the original SE_100_H case, which was run using the old ground temperature method. The same goes for the difference in the efficiency of providing the package of energy services to the house. This indicates that both residential cogeneration system and reference system are more or less equally influenced by the improvement to ESP-r's ground temperature calculation, and that the adjusted energy requirement for domestic hot water has not changed the basis of comparison between residential cogeneration and the reference system. Therefore, there is no problem in using the new ESP-r version for additional simulation runs, in which the difference will be investigated in the results of simulations using generated electricity demand profiles and of those using measured profiles.

5.2 Generated profiles

An electricity demand profile generator has been developed by the NRC and is described in Knight et al. (2007). This generator was used to generate three different (non-HVAC) electricity demand profiles for a Canadian family with an average electricity demand living in a single detached house. All three profiles were generated using identical inputs to the stochastic process of the profile generator. The profiles have a 5 minute time step. Table 5.1 presents the most important characteristics of the profiles. For more details on both the NRC profile generator and the generated profiles the reader is referred to the report from Knight et al. (2007).

5.3 Measured profiles

During the mid 1990s, Hydro Quebec performed an experimental program to assess the impact of energy saving measures in electrically heated houses in Quebec. For 2.5 years, the total cumulative electricity consumption over 15 minute periods was measured, as well as the separate amounts for space heating and for domestic hot water heating. The balance between the total electric consumption and the latter two quantities provided suitable non-HVAC electricity demand profiles for use in building simulation.

Four measured non-HVAC simulation profiles with annual electricity consumption close to that of the generated profiles were selected. The characteristics of these profiles, which have a 15 minute time basis, are also given in Table 5.1.

Table 5.1 Characteristics of generated profiles and measured profiles.

Profile name	Annual electricity consumption (kWh)	Peak electricity consumption (W)	Heating season* electr. consumption (kWh)
Generated profiles			
G1	8218	8313	4790
G2	8112	8760	4802
G3	8160	8808	4861
Measured profiles			
M1	7425	6568	4494
M2	7713	7028	4687
M3	8265	8080	4957
M4	8426	7020	5147

* Heating season is defined here as the period October through April.

5.4 Comparison of results of annual simulations of the Stirling Engine system using generated profiles and measured profiles

The performance of a Stirling engine residential cogeneration system (similar to case SE_100_H) applied in a single detached house in Canada was investigated by performing annual simulations using the three generated electricity demand profiles and the four measured electricity consumption profiles from Table 5.1. For these 7 cases, the reduction of GHG emissions compared to the reference cases using the same electric load profiles is displayed in Figure 5.1. Figure 5.2 presents the improvement of the net house efficiency for coal and natural gas based electricity production compared to the reference cases. More detailed simulation results for all 7 cases can again be found in the appendix. The three cases using generated profiles are labelled SE_100_H_GX (X = 1, 2, and 3). The names of the cases with measured profiles are SE_100_H_MX (X = 1, 2, 3, and 4).

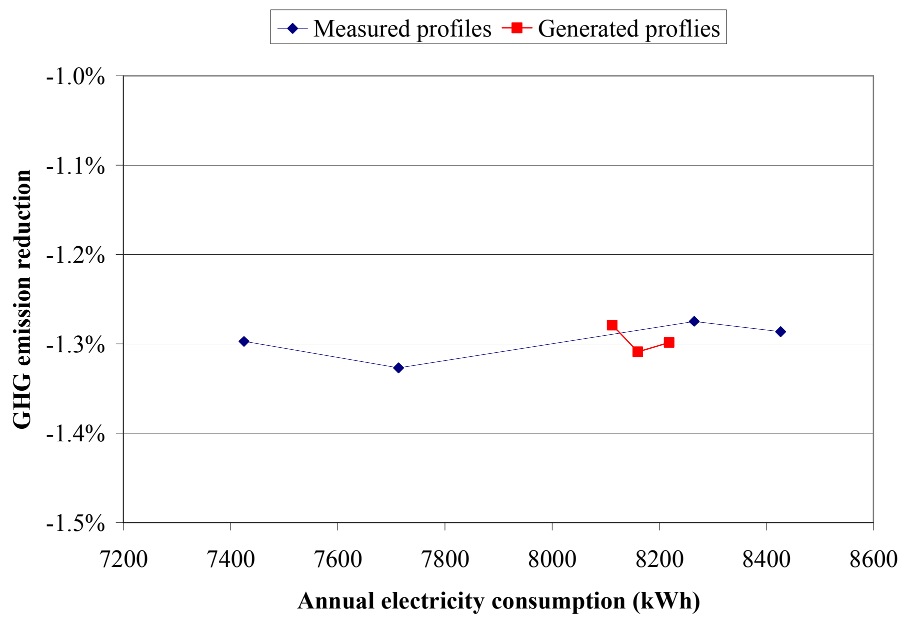


Figure 5.1 Comparison of GHG emission reduction of a Stirling engine based residential cogeneration system using measured profiles and generated profiles (negative values indicate actual emissions increases).

The annual simulations of the Stirling engine system using the generated and measured electricity profiles show very similar results in comparison to the reference cases. All 7 cases increase GHG emissions by around 1.3%, and the decrease in net house efficiency for the cases using the generated profiles are very close to the trend for the cases using measured profiles for both electricity from coal and for natural gas fired power plants as source of grid electricity. These trend lines in Figure 5.2 are caused by the 'feed-back effect' that electricity consumption has on the heat the heating system has to provide for space heating (see section 2.7). In general, higher electricity consumption during the heating season will result in a smaller amount of heat to be provided by the heating system.

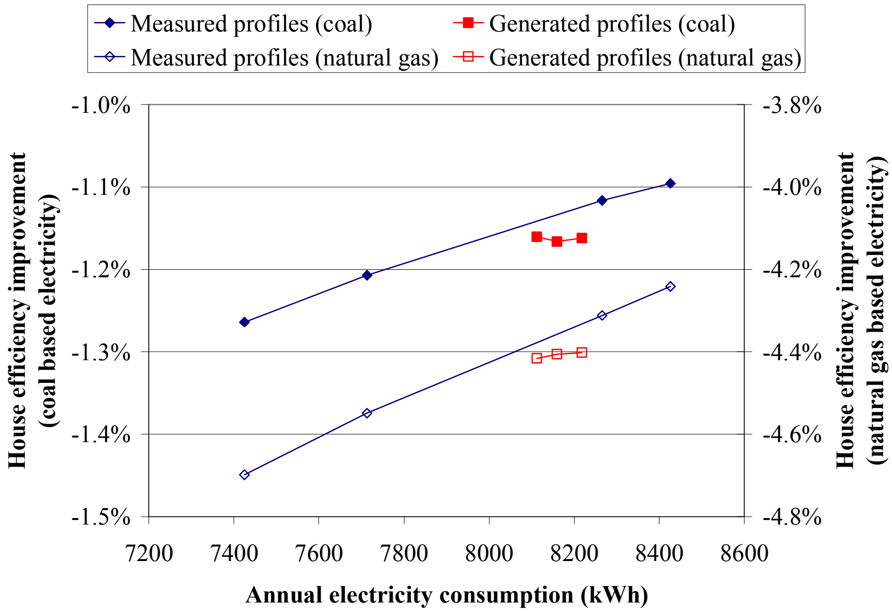


Figure 5.2 Comparison of net house efficiency improvement for a Stirling engine based residential cogeneration system using measured profiles and generated profiles.

The emissions factor of grid electricity varies strongly over time in relation with the fuel sources(s) that are on the margin (Mottillo at al 2006). It is therefore most likely that the small variation in the GHG emission reduction for the 7 cases is caused by the difference in displaced emissions for on-site produced electricity due to different operation schedules of the residential cogeneration systems.

The differences between the net house efficiencies for the cases using generated profiles and the trend line for the measured profiles are very small, of the order of 0.1%-point. Figure 5.3 displays a potential cause for these differences: The cases using the generated profiles appear to benefit less from the casual gain from electricity consumption than the cases with the measured profiles. However, more detailed investigation is required to explain this difference based upon e.g. the difference in 'peakiness' between the two sets of profile and/or the different time bases of the generated and measured profiles. These investigations may result in general conclusions on the use of these sets of generated and measured profiles in building simulation studies. This work, however, is outside the scope of the current study.

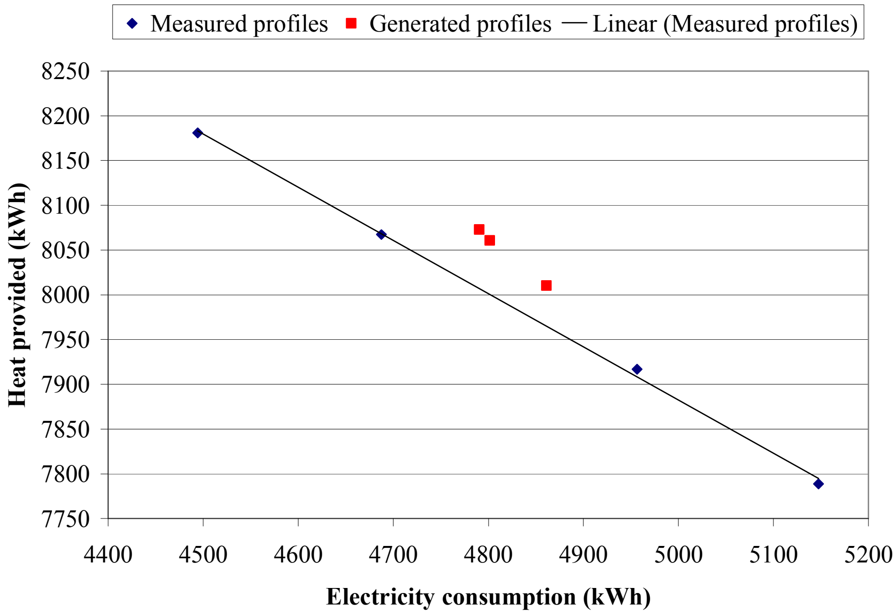


Figure 5.3 Relation between electricity consumption and heat provided for space heating during the heating season using measured and generated electricity consumption profiles.

6 GREENHOUSE GAS MINIMIZATION CONTROLLER

In the performance assessment study presented in this report, the greenhouse gas emissions of the investigated residential cogeneration systems have been a result of the chosen operating mode for the specific systems. In a scenario in which GHG emissions should strictly be minimized, a 'greenhouse gas minimization controller' could actively influence the mode of operation of the residential cogeneration system to ensure that the energy demands of the house would be met with minimum GHG emissions from the residential cogeneration system and/or grid electricity. The implementation of a first concept of such a controller is described in this chapter.

6.1 Introduction

In general, residential cogeneration systems will have more or less constant greenhouse gas (GHG) emissions over the year. Although the *total* of the GHG emissions will be higher over the winter period than over the summer period, the emissions *per unit of output*, i.e. the emissions related to the production of for instance 1 kWh of electricity, will roughly be the same throughout the year. Small differences in efficiency can exist due to variation of inlet air and cooling water temperature over the seasons.

The GHG emissions of on-the-margin electricity are *not* constant over the year, but vary considerably with the on-the-margin fuel sources (Mottillo et al. 2006). When hydropower is on the margin, the GHG emissions will almost be negligible, while the GHG emissions of coal-fired power production are substantial.

A 'greenhouse gas minimization controller' can explore these differences in GHG emissions of the residential cogeneration systems and the grid electricity to minimize the overall GHG emissions related to the energy consumption of the house. When the GHG emissions of the residential cogeneration system will be lower than those of the on-the-margin grid electricity, the residential cogeneration system is used, while electricity will be imported from the grid when the on-the-margin power is cleaner.

6.2 Implementation of first concept

A first version of a GHG emission minimization controller was implemented in ESP-r. This version does not yet take into account the full complexity of comparing the emissions of a residential cogeneration system and those of a reference system (grid electricity and back-up heater), but is focused on emissions from electricity production for now. Every time step, the controller calculates whether the use of the residential cogeneration unit (at full load, 50% load, or minimum load) will displace more emissions of the on-the-margin fuel source(s) than it will produce itself. If so, the residential cogeneration unit will be used at the highest load that will bring emission reduction, otherwise electricity will be imported from the grid. To prevent heat dump from the system, the controller only activates the residential cogeneration system if the temperature of the hot water storage tank is sufficiently low that the heat added to the tank would not be rejected.

6.3 Example

The operation of the GHG emission minimization controller is demonstrated below through an example of an SOFC residential cogeneration system (similar to the one used for the SOFC_100 case).

The top part of the figure shows the displaced on-the-margin grid emissions and the emissions of the residential cogeneration system for full load, 50% load, and minimum load for one day. Whenever the displaced emissions of grid electricity will surpass the emissions of the cogeneration unit, the controller will activate the cogeneration unit. The control signal is given in the bottom part, its value representing the range between full load (1.00) and off (0.00). The controller follows the trend of the weighted emission factor of the on-the-margin fuel source(s), which is also displayed in the bottom part of the figure.

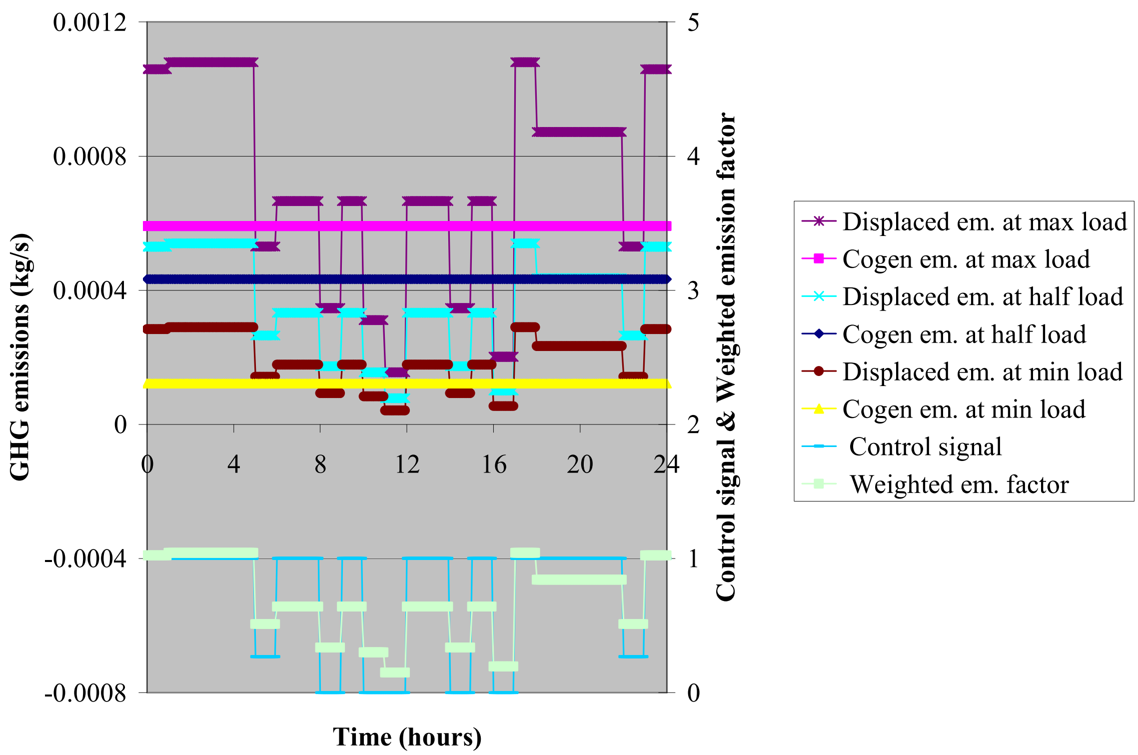


Figure 6.1 Example of the operation of the GHG emission minimization controller.

It should be stated clearly that the results displayed in Figure 6.1 are for *illustrational* purposes only! The Annex 42 SOFC model has been used outside the range of operating conditions it was calibrated for. Therefore no value should be given to the parameter values displayed or their differences.

7 CONCLUSIONS AND RECOMMENDATIONS

The performance of prototype residential cogeneration systems based upon the Stirling engine (SE) and Solid Oxide Fuel Cell (SOFC) technologies and applied in single detached houses in Canada has been investigated using calibrated models developed in Subtask B of Annex42. The SOFC systems were run in continuous operation with a 3-month summer stop, while the operation of the SE systems was investigated for both a heat load following mode and an electric load following mode. The results of annual simulations using the whole-building simulation program ESP-r show that the SE systems perform consistently better in heat led operation than in electric load following mode, due to reduced efficiencies at part load operation.

For the prototype devices investigated, the Greenhouse gas (GHG) emission reduction potential is mainly determined by the displaced emissions of the grid. Application of the prototype SOFC system in Ontario would substantially reduce the GHG emissions of the house despite a very low net cogeneration system efficiency of 37%. The prototype SE system has a higher system efficiency but negligible GHG emission reduction when applied in heat load following operation in Ontario. The prototype cogeneration units in this study would cause GHG emissions to increase when applied in Québec, Alberta, and British Columbia.

The heat led SE system consumes between 5% - 10% more natural gas than the reference system, a difference that may already be bridged by relatively easy measures like reducing heat storage losses (more and/or better insulation) and BOP power consumption (high efficiency DC-motor pumps). The SOFC needs 50% - 150% additional natural gas input compared to the reference system, partly due to the necessity to dump excess heat. Improvements to both SE and SOFC prototype systems are possible that will allow the systems to reduce the primary energy input to the house and have substantial GHG emission reductions.

The electric capacity of the SE unit (0.7 kWe) is rather small for Canadian single detached houses, the SOFC capacity (2.8 kWe) is too large (assuming continuous operation at nominal power).

The importance of performing detailed simulations with small time steps was demonstrated by this study. For the heat led SE cogeneration system, stand-still losses and HVAC electricity reduced the net electric system efficiency to only 64% of full load efficiency. The net heat efficiency was 81% of full load efficiency.

For the base case Stirling engine residential cogeneration system applied in a single detached house in Canada, simulations performed with *generated* electricity demand profiles show results that are very close to those of simulations using *measured* profiles. Additional detailed research is recommended to investigate whether this conclusion can be expanded to the general use of these profiles.

A first version of a GHG emission minimization controller was successfully implemented in ESP-r. More work is needed to have the controller address the full complexity of using residential cogeneration, grid electricity, and a back-up heat source to minimize overall GHG emissions of a house.

The current study has focused on the measured performance of *prototype* residential cogeneration systems. These prototypes

- had efficiencies well below those expected for mature technology,
- had unsophisticated operating strategies that could be vastly improved (SOFC), and
- had inappropriate electrical capacities (SE was too small, SOFC too large).

The results of this study provide a ‘snapshot’ of the development of residential cogeneration systems, which is certainly not representative of the *potential* of the technologies. The report contains valuable information for designers of residential cogeneration systems in relation to the optimization of their systems, but should not be used to form an opinion on the potential impact of these technologies. It is necessary and recommended to further investigate the potential of residential cogeneration technologies in Canada using either detailed performance characteristics of more mature versions of the cogeneration systems currently in development, or performance figures that represent a realistic view of the future potential of these technologies.

8 ACKNOWLEDGEMENT

The work described in this report was undertaken as part of the IEA/ECBCS Annex 42 (www.cogen-sim.net). The Annex is an international collaborative research effort and the authors gratefully acknowledge the indirect or direct contributions of other Annex participants.

M. Thomas and A. Parekh of Natural Resources Canada, Ottawa are acknowledged for their expert information on water heaters and building standards.

I. Beausoleil-Morrison, V. Doror, A. Hawkes, M. Sasso, and S. Sibilio of Annex 42 and M. Atif and T. Sawachi of the IEA/ECBCS Executive Committee are specifically thanked for their efforts in reviewing the report.

9 REFERENCES

Beausoleil-Morrison I, Schatz A, Maréchal F. 2006a. “A Model for Simulating the Thermal and Electrical Production of Small-Scale Solid-Oxide Fuel Cell Cogeneration Systems within Building Simulation Programs”, HVAC&R Research, Vol. 12, No. 3a, pp.641-667.

Beausoleil-Morrison I, Schatz A, Maréchal F. 2006b. “On Methods for Calibrating the Thermal and Electrical Production of Small-Scale Solid-Oxide Fuel Cell Cogeneration Systems”, in Proc. 7th Int. Conf. on System Simulation in Buildings, Liège Belgium.

Beausoleil-Morrison I. (ed). 2007. “Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models”, IEA/ECBCS Annex 42.

Beausoleil-Morrison, I. and Kelly, N. (eds). 2007. “Specifications for Modelling Fuel Cell and Combustion-Based Residential Cogeneration Device within Whole-building Simulation Programs,” IEA/ECBCS Annex 42 Report.

Bell M, Swinton M, Entchev E, Gusdorf J, Kalbfleisch W, Marchand R, Szadkowski F. 2003. “Development of Micro Combined Heat and Power Technology Assessment Capability at the Canadian Centre for Housing Technology”, Canadian Centre for Housing Technology.

Carbon Trust. 2005. “The Carbon Trust’s Small-Scale CHP Field Trial Update”, Carbon Trust, London, United Kingdom.

CCHT 2007. http://www.ccht-cctr.gc.ca/main_e.html

Clarke J.A. 2001. “Energy Simulation in Building Design”, Butterworth-Heinemann, Oxford, United Kingdom.

Dorer V. 2007. “Review of Existing Residential Cogeneration Performance Assessments and Evaluations”, IEA/ECBCS Annex 42 Report.

Dorer V. and Weber A. 2007. “Methodology for the Performance Assessment of Residential Cogeneration Systems”, IEA/ECBCS Annex 42 Report.

Entchev E, Gusdorf J, Swinton M, Bell M, Szadkowski F, Kalbfleisch W, Marchand R. 2004. "Micro-Generation Technology Assessment for Housing Technology", Energy and Buildings, Volume 36, Issue 9, 925-931.

Gamanet 2007. http://www.gamanet.org/gama/infore sources.nsf/vContentEntries/Product+Directories

Hawkes A. and Leach M. 2005. "Impacts of Temporal Precision in Optimisation Modelling of Micro-Combined Heat and Power", Energy, Volume 30, Issue 10, 1759-1779.

ICF Consulting 2003. "Analysis of electricity dispatch in Canada. Final report."

Jordan U, Vajen K. 2001. "Realistic Domestic Hot Water Profiles in Different Time Scales", Universität Marburg, Germany.

Knight I, Kreutzer N, Manning M, Swinton M, Ribberink H. 2007. "European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems", IEA ECBCS/Annex 42 Report.

Mottillo M, Beausoleil-Morrison I, Ferguson A, Ribberink H, Yang L, Haddad K. 2006. "Examining the Feasibility of a Hydrogen-Based Renewable Energy-Powered Residential Cogeneration System for Grid-Connected Houses", Natural Resources Canada Internal Report.

Numerical Logics. 1999. "Canadian Weather for Energy Calculations, Users Manual and CD-ROM", Downsview, Ontario: Environment Canada.

Purdy J. and Beausoleil-Morrison I. 2001. "The Significant Factors in Modelling Residential Buildings", Proceedings of the 7th IBPSA Conference, Rio de Janeiro, Brazil, pp. 207-214.

OEE 2007. http://oee.nrcan.gc.ca/corporate/statis tics/neud/dpa/comprehensive_tables/index.cfm

Ribberink H, Bourgeois D, Beausoleil-Morrison I. 2007. "Performance Assessment of Residential Cogeneration Systems in Canada Using a Whole-Building Simulation Approach", Proceedings of the 10th International Building Performance Simulations Association Conference, Beijing, China, September 2007.

10 NOMENCLATURE

$DE_{Fuel\text{-}BB}$	Energy content (HHV) of fuel consumed by back-up burner
$DE_{Fuel\text{-}CGU}$	Energy content (HHV) of fuel consumed by cogeneration unit.
$GHG_{CGS,f}$	GHG emission factor for electricity production cogeneration system
$GHG_{CGS,total}$	Total GHG emission of the cogeneration system (SE/SOFC and back-up burner)
$GHG_{ref,SH+DHW}$	Combined GHG emission of the furnace and the hot water heater for the reference case
NE_{DHW}	Thermal energy supplied to meet domestic hot water demand
$NE_{El\text{-}BOP}$	Electricity consumption of balance of plant equipment (pumps only)
$NE_{El\text{-}BOP,extra}$	Additional power consumption for BOP equipment of the cogeneration system over that for the reference system.
$NE_{El\text{-}non\text{-}HVAC}$	Non-HVAC electricity demand
NE_{SH}	Thermal energy supplied to meet space heating demand (after casuals gains have been accounted for)
$OE_{El\text{-}CGU,net}$	Net AC power output cogeneration unit
$OE_{Th\text{-}HS,dump}$	Heat dumped from storage tank
$OE_{Th\text{-}CGU,gross}$	Gross heat output from the cogeneration unit
$PE_{El\text{-}grid}$	Primary energy input to the central power plant
$\eta_{HHV,CGS,net}$	Net efficiency of cogeneration system
$\eta_{HHV,CGU,net}$	Net efficiency of cogeneration unit
$\eta_{HHV,El\text{-}CGS,net}$	Net electric efficiency of cogeneration system
$\eta_{HHV,El\text{-}CGU,net}$	Net electric efficiency of cogeneration unit
$\eta_{HHV,house,net}$	Net efficiency of supplying electricity, space heating, and DHW to the house
$\eta_{HHV,Th\text{-}CGS,net}$	Net thermal efficiency of cogeneration system
$\eta_{HHV,Th\text{-}CGU,gross}$	Gross thermal efficiency of cogeneration unit
$\eta_{HHV,Th\text{-}CGU,net}$	Net thermal efficiency of cogeneration unit

APPENDIX: OVERVIEW OF SIMULATION RESULTS PER CASE

Results of simulation cases are presented in the following order:

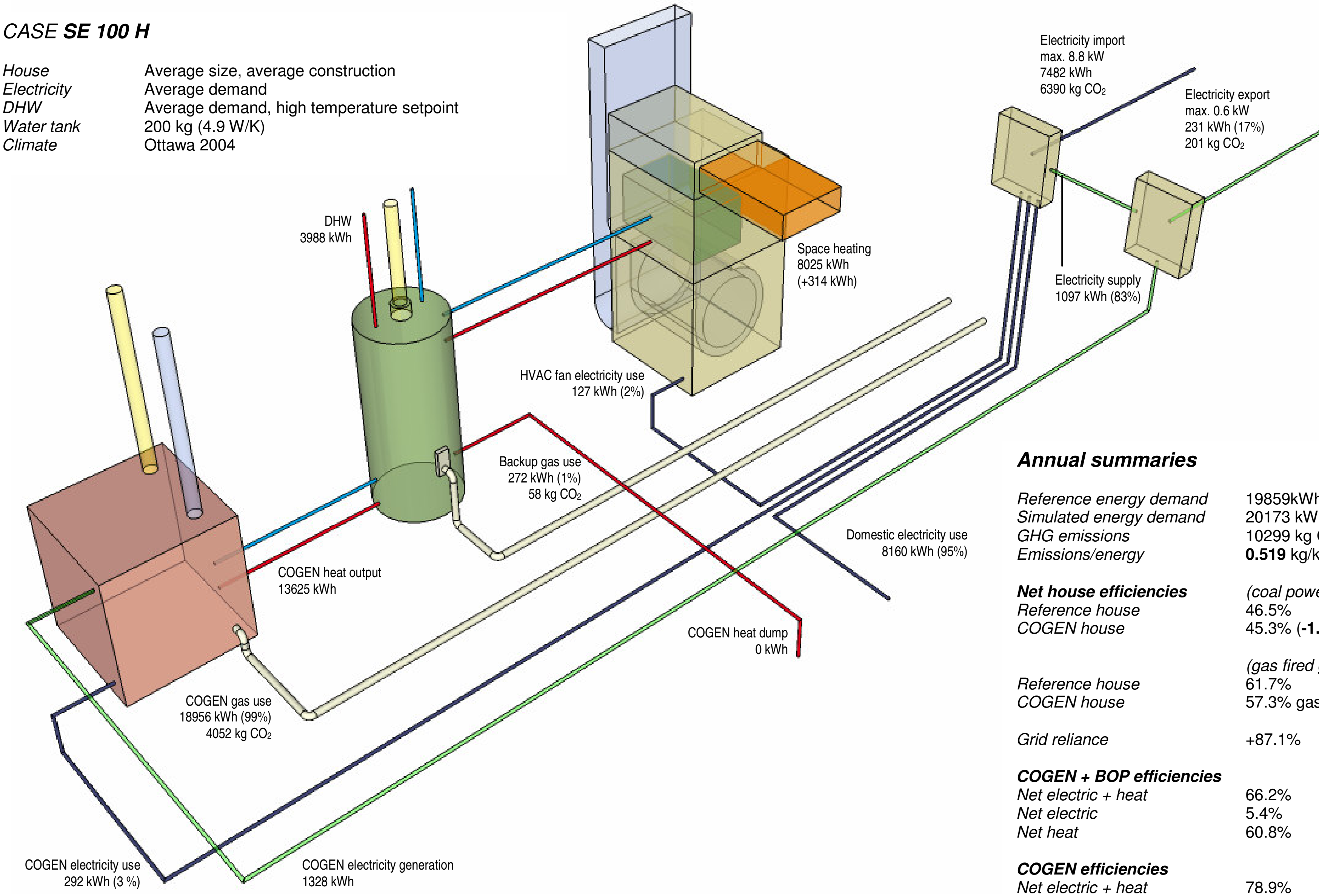
• SE_100_H – SE_840_H	SE cases with heat load following operation
• SE_100_E – SE_840_E	SE cases with electric load following operation
• SOFC_100 – SOFC_840	SOFC cases
• SE_100_H_G1 – SE_100_H_G3	Additional cases with generated elec. load profiles
• SE_100_H_M1 – SE_100_H_M4	Additional cases with measured elec. load profiles

For each case, an information block starting with 'Annual summaries' contains the most important results regarding emissions and efficiencies. In this:

- The 'Reference energy demand' and the 'Simulated energy demand' present the sum of the total annual demands for space heating, DHW, and electricity for the reference system and the cogeneration system, respectively.
- The 'Emissions/energy' is the simulated energy demand for the cogeneration system divided by the GHG emissions. This parameter is also displayed in the graph in the bottom right corner.
- The 'Grid reliance' is the grid import for the cogeneration case divided by the grid import for the corresponding reference case. This parameter will have negative values for SOFC cases with a net power export.
- For the definitions of efficiencies of the cogeneration unit, cogeneration system, and the house, the reader is referred to section 3.2.

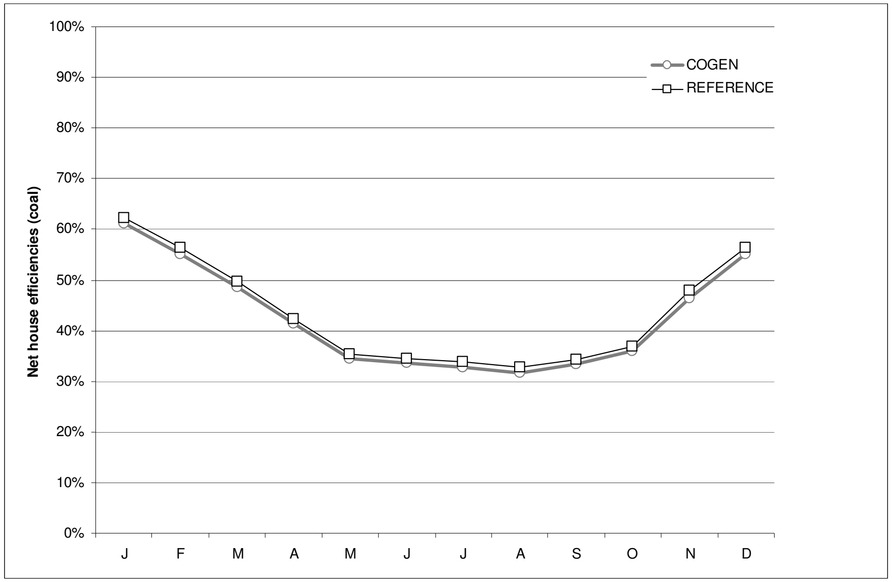
CASE ***SE 100 H***

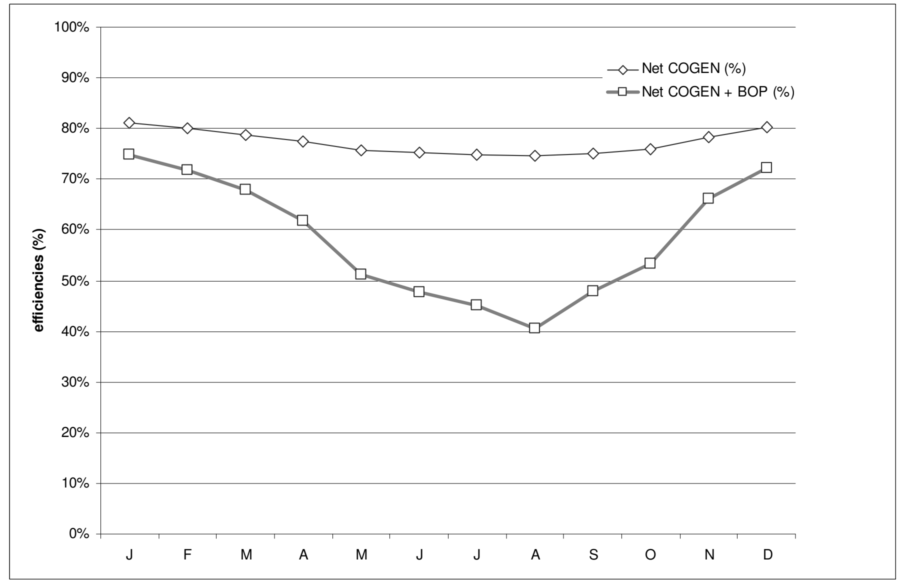
House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004

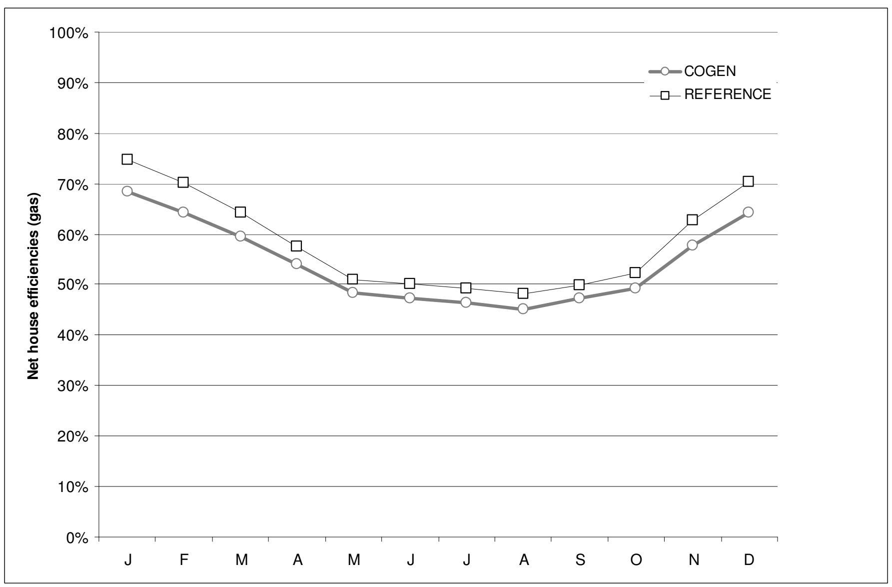


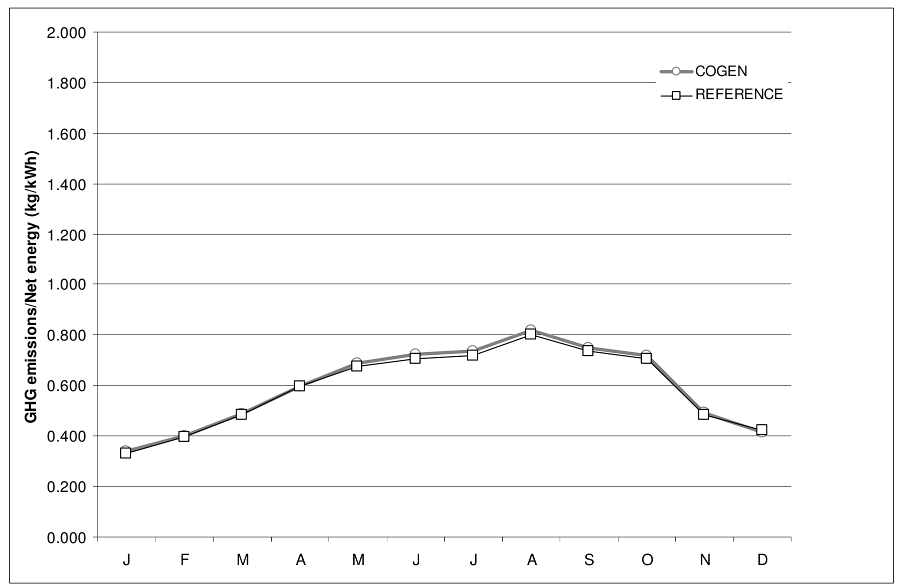
Annual summaries

Reference energy demand	19859kWh
Simulated energy demand	20173 kWh (**+1.6%**)
GHG emissions	10299 kg CO_2 (**+1.4%**)
Emissions/energy	**0.519** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	45.3% (**-1.2%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	57.3% gas (**-4.4%-p.**)
Grid reliance	+87.1%
COGEN + BOP efficiencies	
Net electric + heat	66.2%
Net electric	5.4%
Net heat	60.8%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%







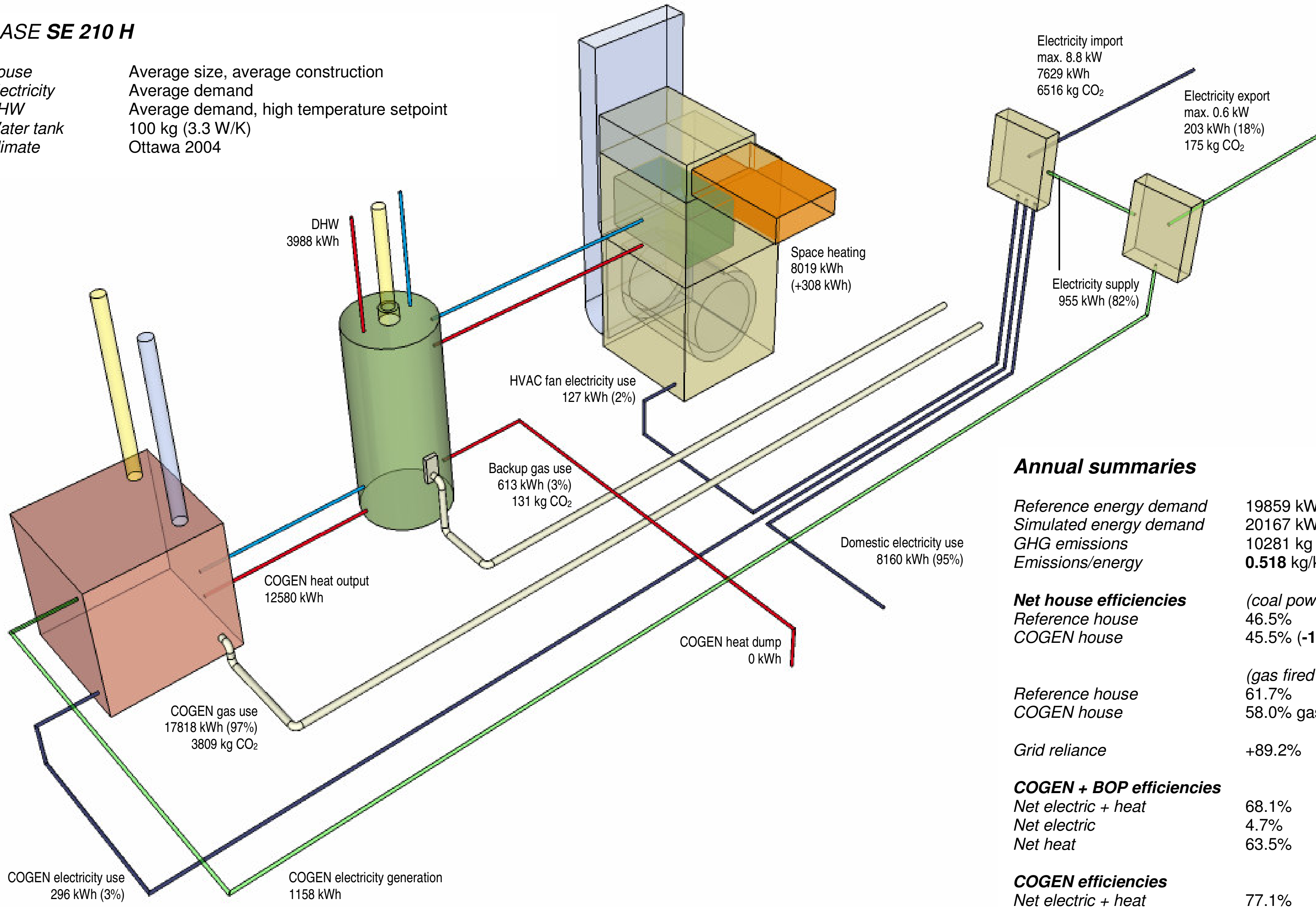


CASE SE 100 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

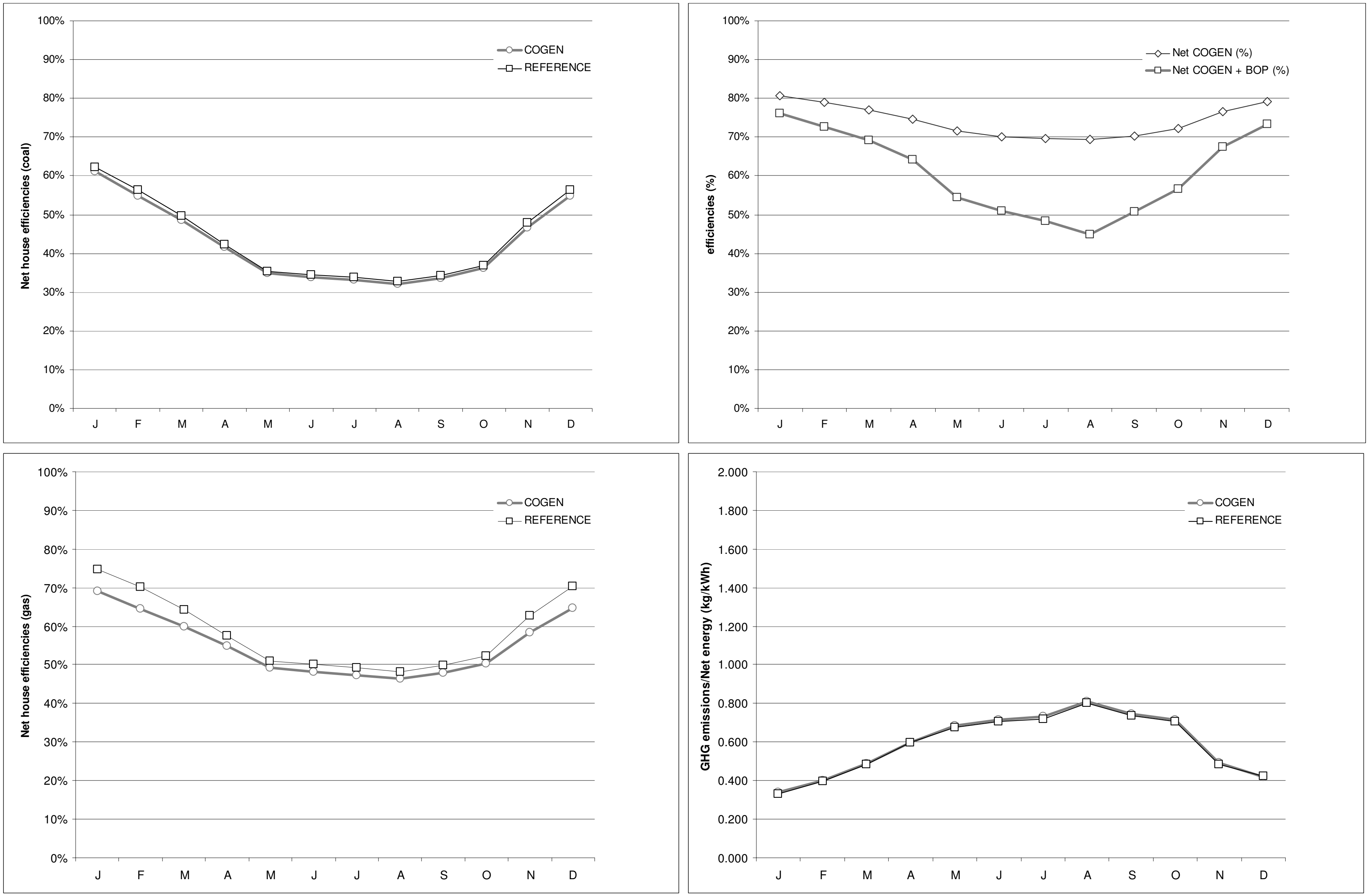
CASE ***SE 210 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	100 kg (3.3 W/K)
Climate	Ottawa 2004



Annual summaries

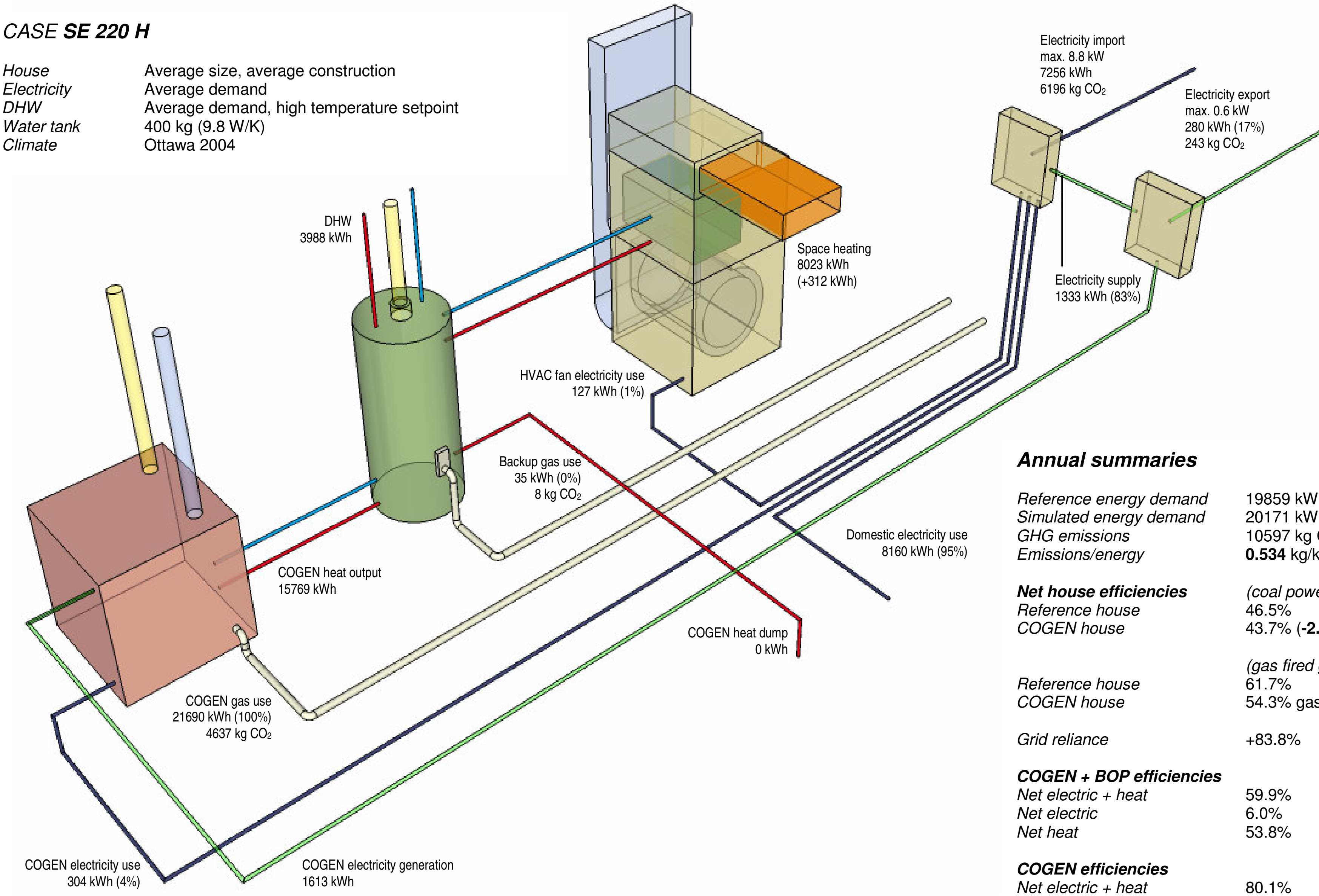
Reference energy demand	19859 kWh
Simulated energy demand	20167 kWh (**+1.6%**)
GHG emissions	10281 kg CO_2 (**+1.2%**)
Emissions/energy	**0.518** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	45.5% (**-1.0%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	58.0% gas (**-3.7%-p.**)
Grid reliance	+89.2%
COGEN + BOP efficiencies	
Net electric + heat	68.1%
Net electric	4.7%
Net heat	63.5%
COGEN efficiencies	
Net electric + heat	77.1%
Net electric	6.5%
Gross heat	70.6%
Net heat	70.6%
COGEN heat dump/output	0.0%



CASE SE 210 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

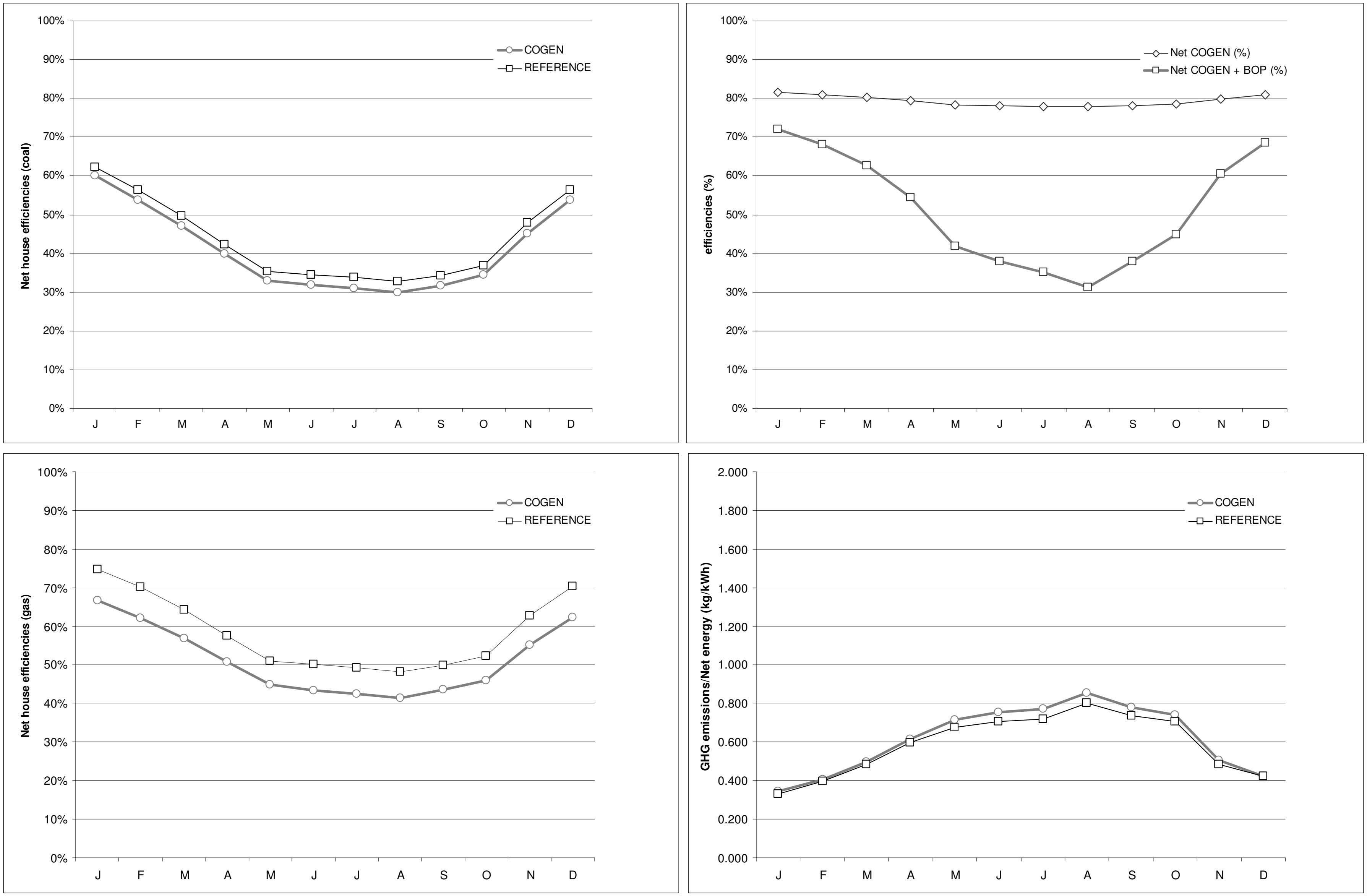
CASE ***SE 220 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	400 kg (9.8 W/K)
Climate	Ottawa 2004



Annual summaries

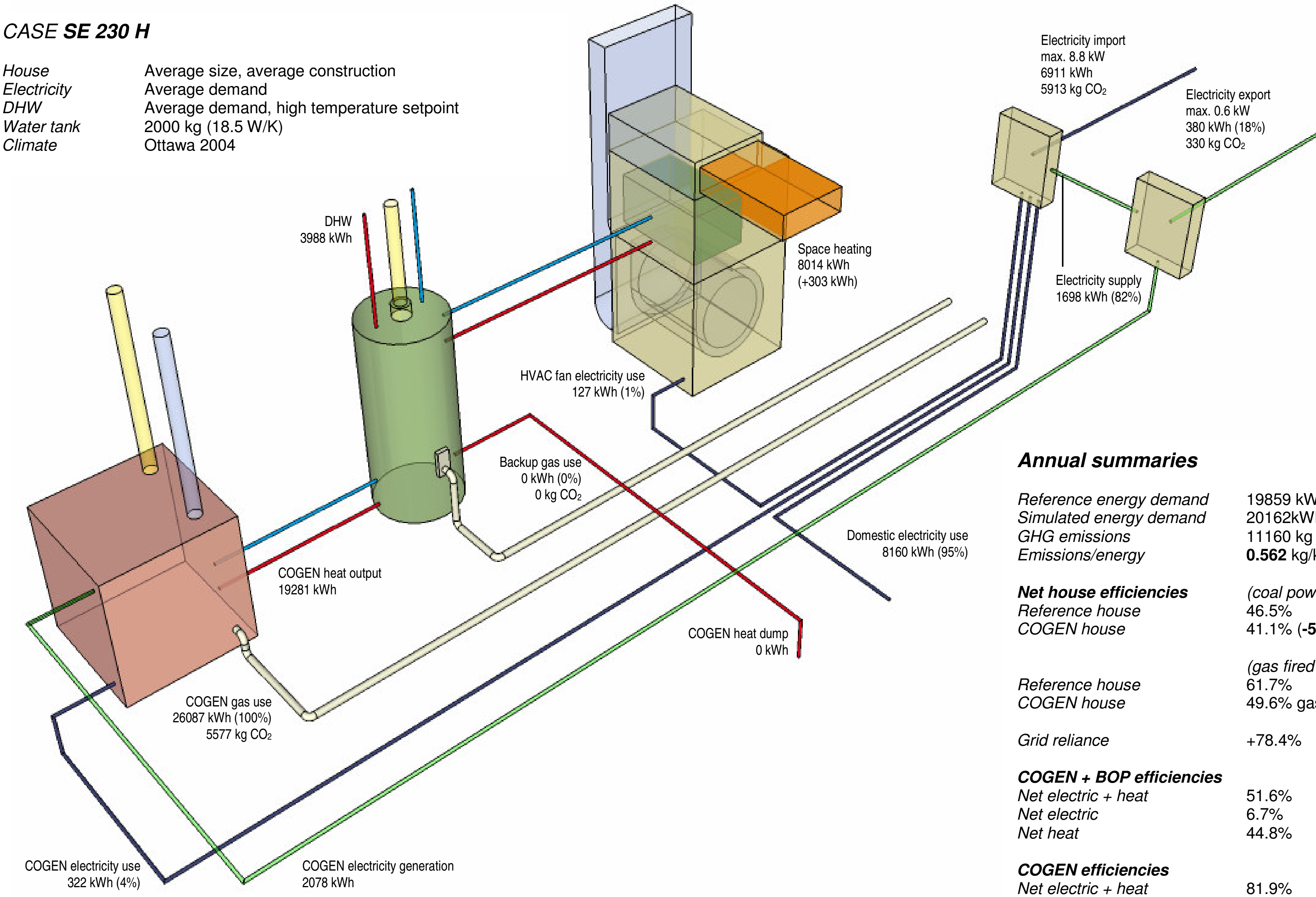
Reference energy demand	19859 kWh
Simulated energy demand	20171 kWh (**+1.6%**)
GHG emissions	10597 kg CO_2 (**+4.3%**)
Emissions/energy	**0.534** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	43.7% (**-2.8%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	54.3% gas (**-7.4%-p.**)
Grid reliance	+83.8%
COGEN + BOP efficiencies	
Net electric + heat	59.9%
Net electric	6.0%
Net heat	53.8%
COGEN efficiencies	
Net electric + heat	80.1%
Net electric	7.4%
Gross heat	72.7%
Net heat	72.7%
COGEN heat dump/output	0.0%



CASE SE 220 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

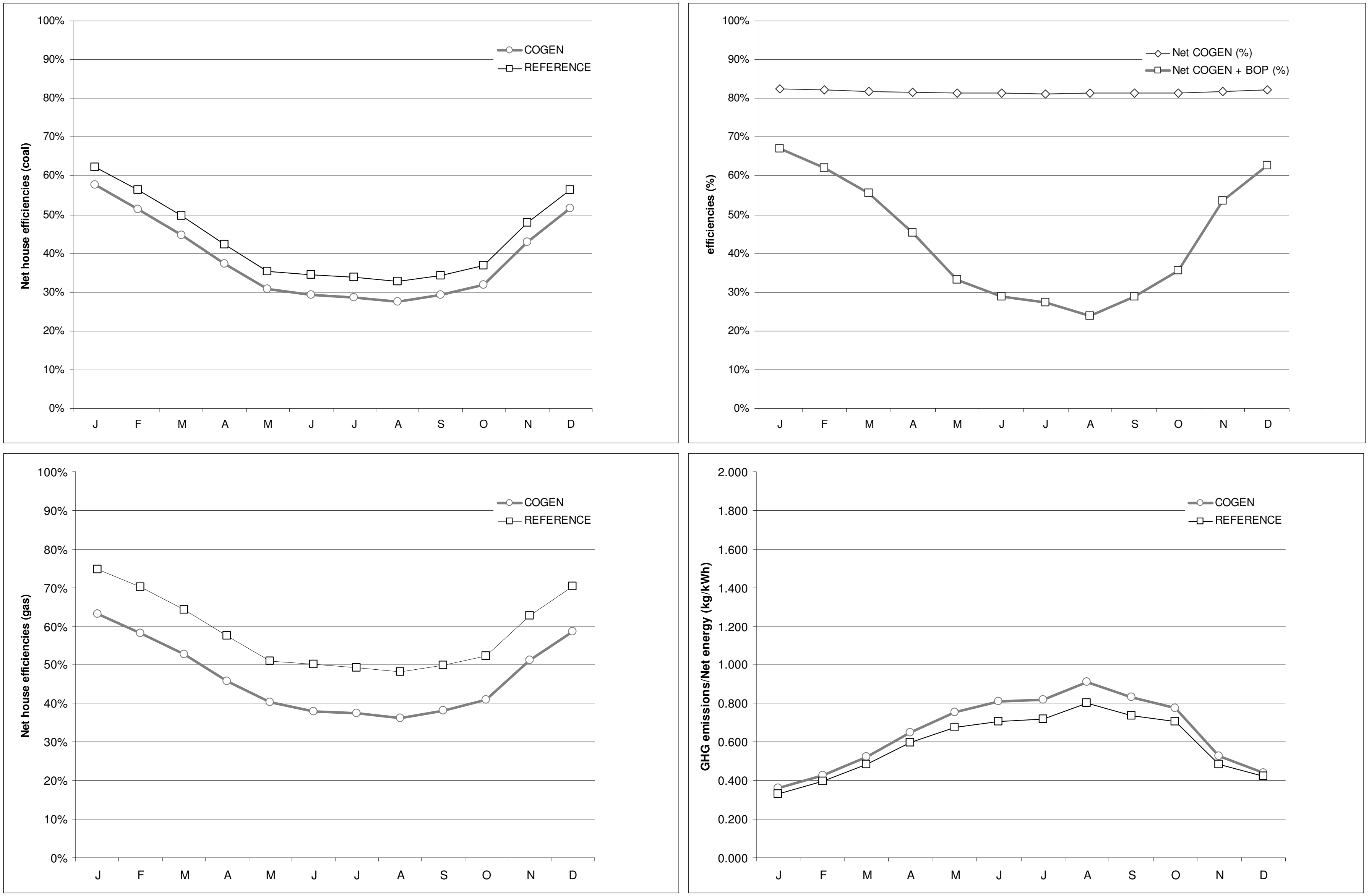
CASE ***SE 230 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	2000 kg (18.5 W/K)
Climate	Ottawa 2004



Annual summaries

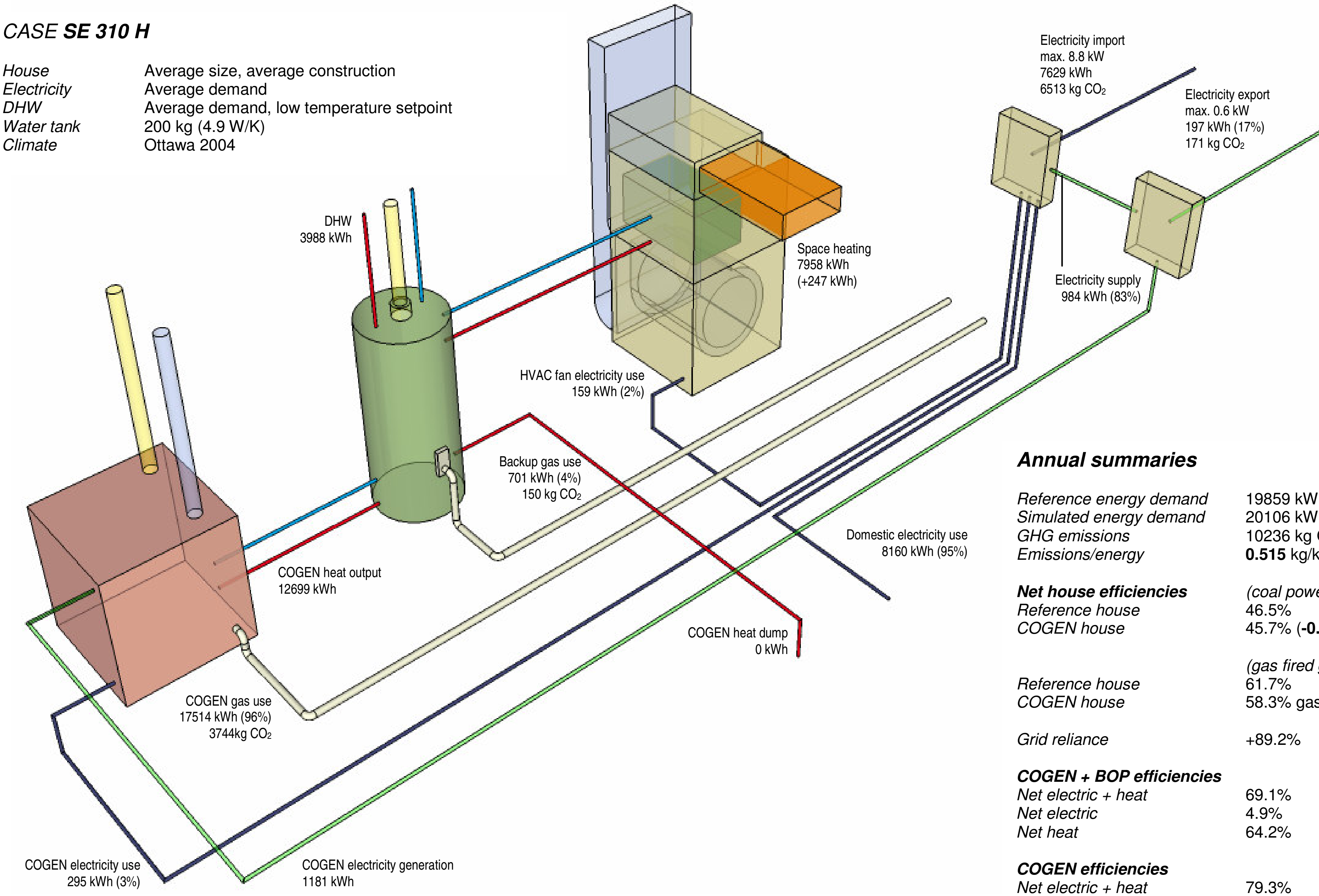
Reference energy demand	19859 kWh
Simulated energy demand	20162kWh (**+1.5%**)
GHG emissions	11160 kg CO_2 (**+9.9%**)
Emissions/energy	**0.562** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	41.1% (**-5.3%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	49.6% gas (**-12.1%-p.**)
Grid reliance	+78.4%
COGEN + BOP efficiencies	
Net electric + heat	51.6%
Net electric	6.7%
Net heat	44.8%
COGEN efficiencies	
Net electric + heat	81.9%
Net electric	8.0%
Gross heat	73.9%
Net heat	73.9%
COGEN heat dump/output	0.0%



CASE SE 230 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

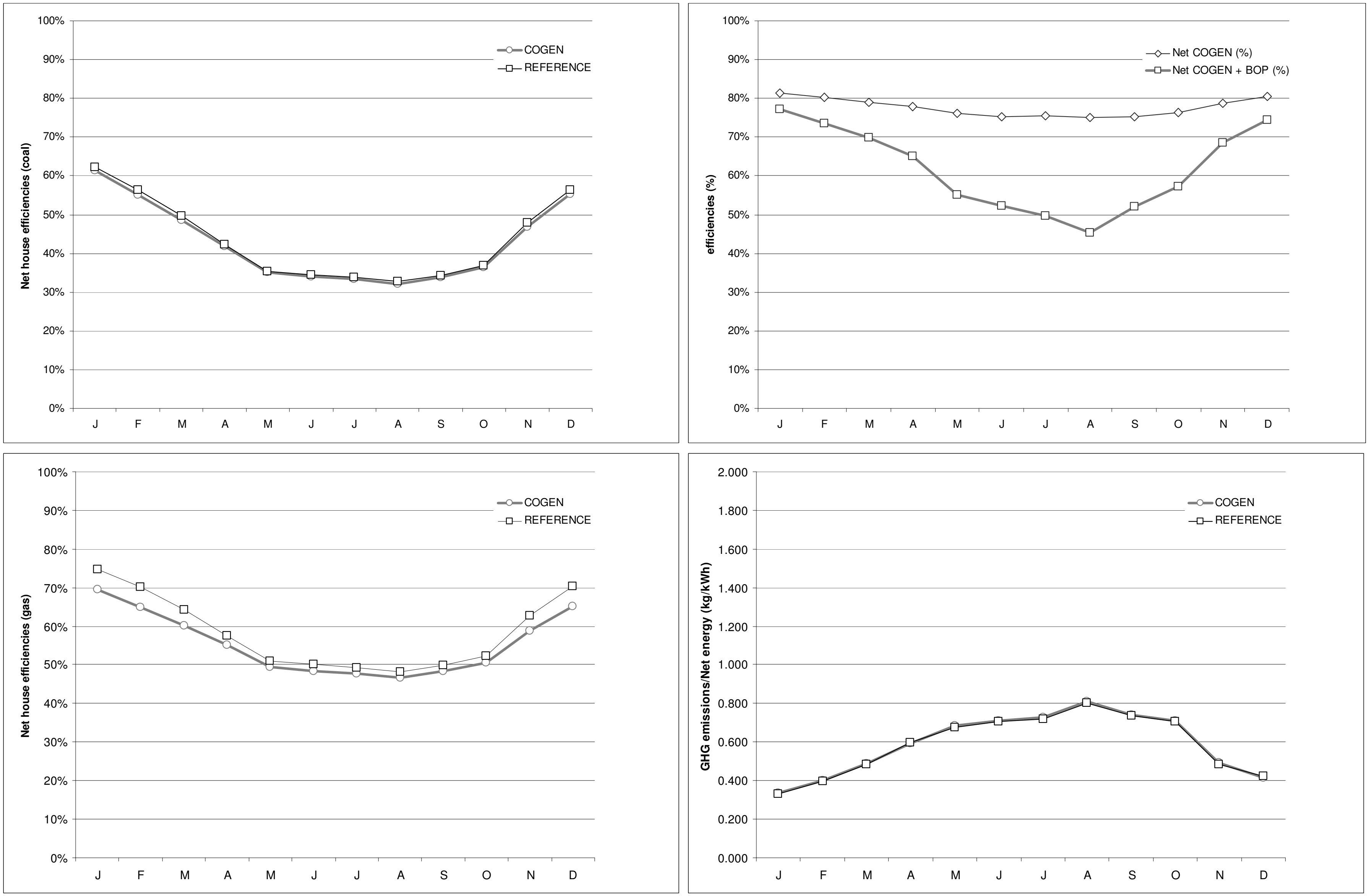
CASE ***SE 310 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, low temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

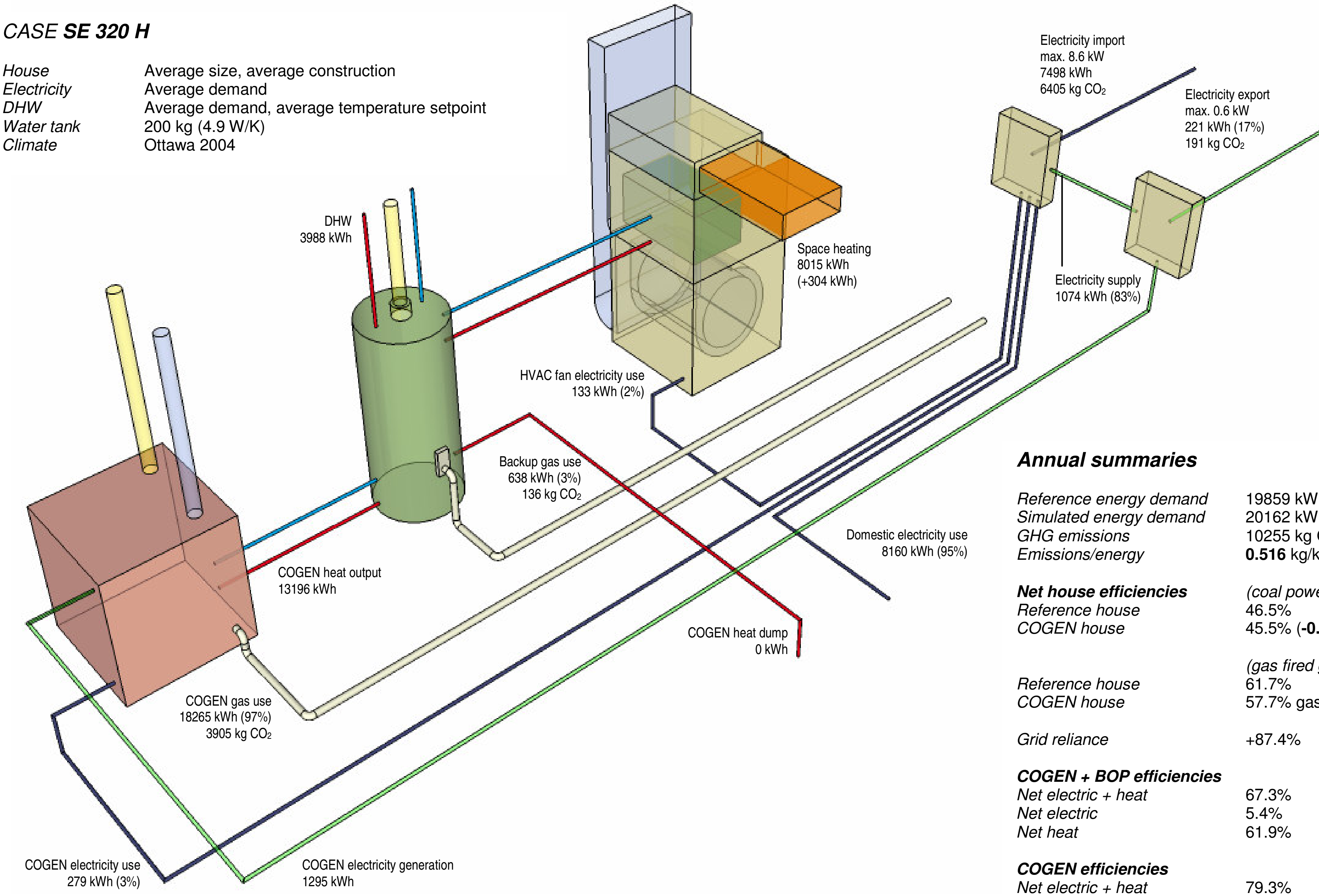
Reference energy demand	19859 kWh
Simulated energy demand	20106 kWh (**+1.2%**)
GHG emissions	10236 kg CO_2 (**+0.8%**)
Emissions/energy	**0.515** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	45.7% (**-0.8%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	58.3% gas (**-3.4%-p.**)
Grid reliance	+89.2%
COGEN + BOP efficiencies	
Net electric + heat	69.1%
Net electric	4.9%
Net heat	64.2%
COGEN efficiencies	
Net electric + heat	79.3%
Net electric	6.7%
Gross heat	72.5%
Net heat	72.5%
COGEN heat dump/output	0.0%



CASE SE 310 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

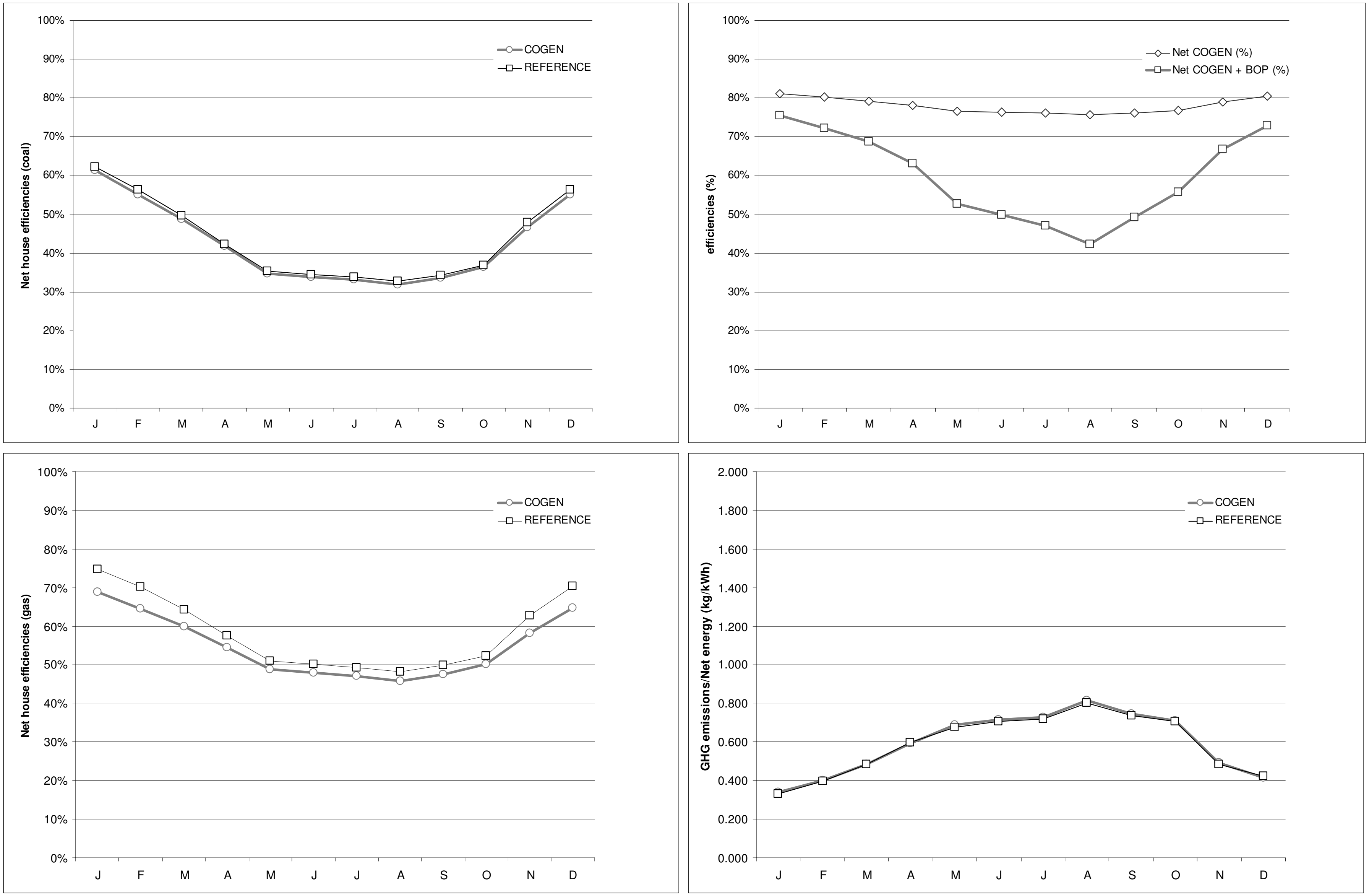
CASE ***SE 320 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, average temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

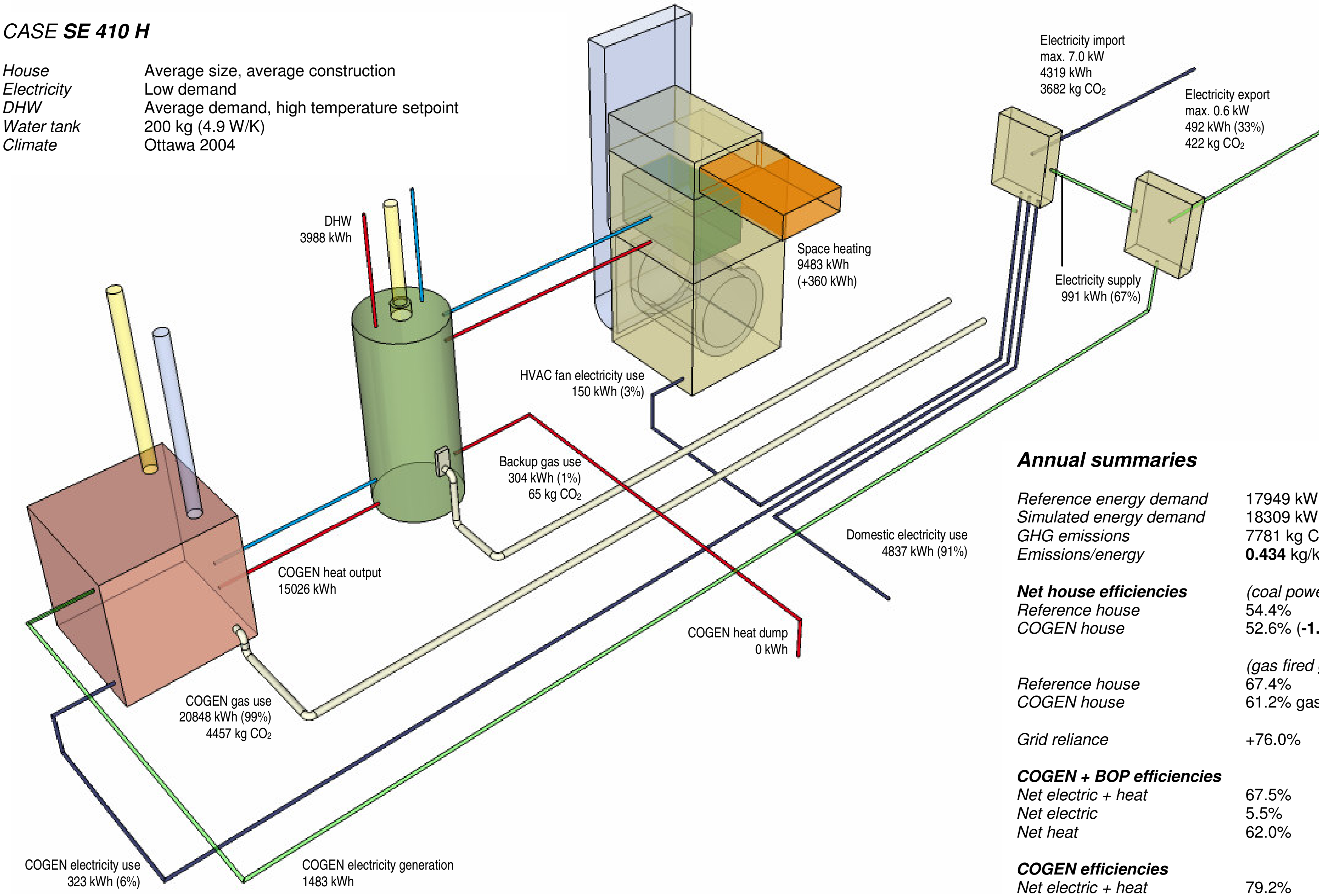
Reference energy demand	19859 kWh
Simulated energy demand	20162 kWh (**+1.5%**)
GHG emissions	10255 kg CO_2 (**+1.0%**)
Emissions/energy	**0.516** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	45.5% (**-0.9%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	57.7% gas (**-4.0%-p.**)
Grid reliance	+87.4%
COGEN + BOP efficiencies	
Net electric + heat	67.3%
Net electric	5.4%
Net heat	61.9%
COGEN efficiencies	
Net electric + heat	79.3%
Net electric	7.1%
Gross heat	72.2%
Net heat	72.2%
COGEN heat dump/output	0.0%



CASE SE 320 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

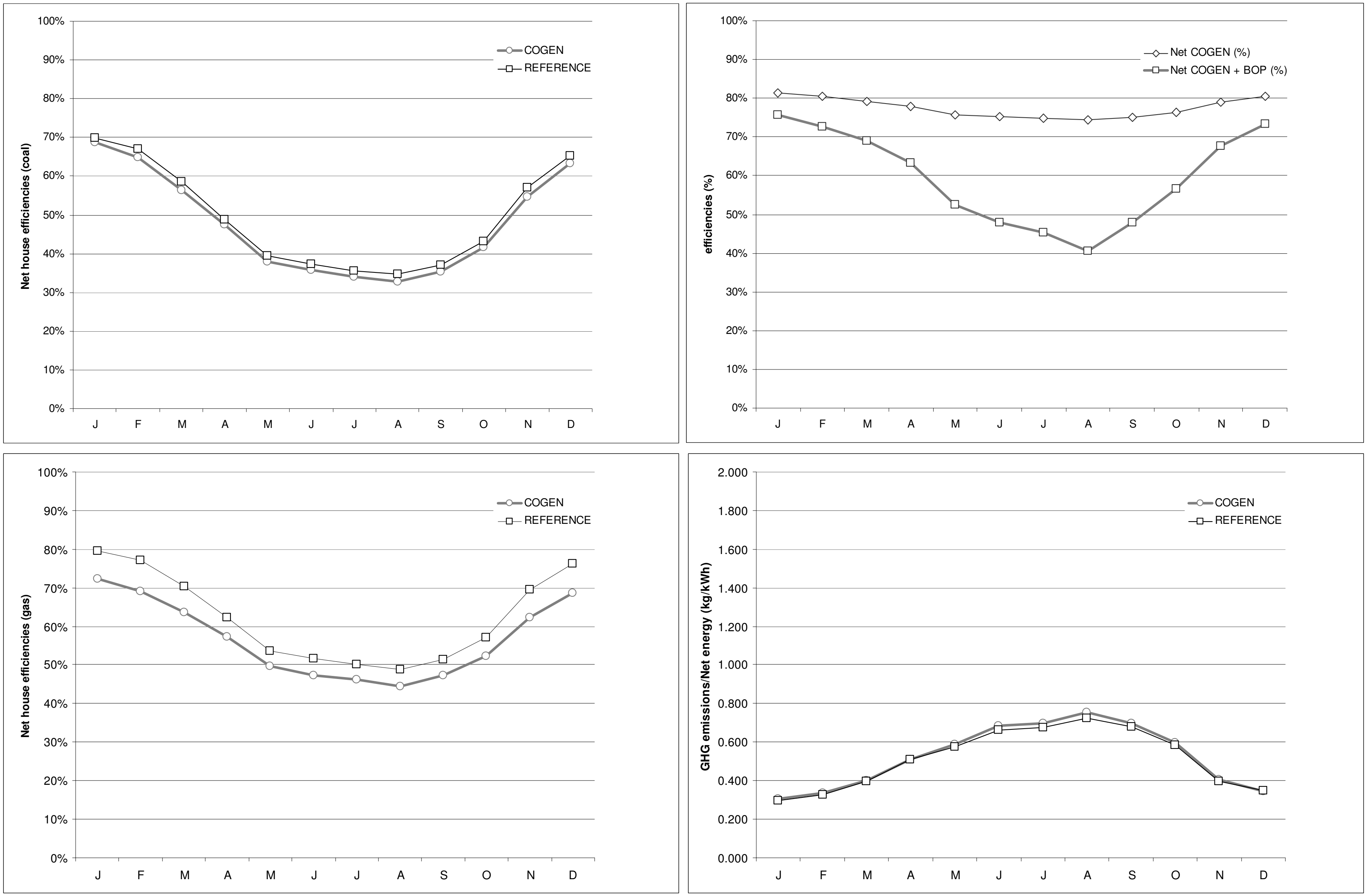
CASE ***SE 410 H***

House	Average size, average construction
Electricity	Low demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

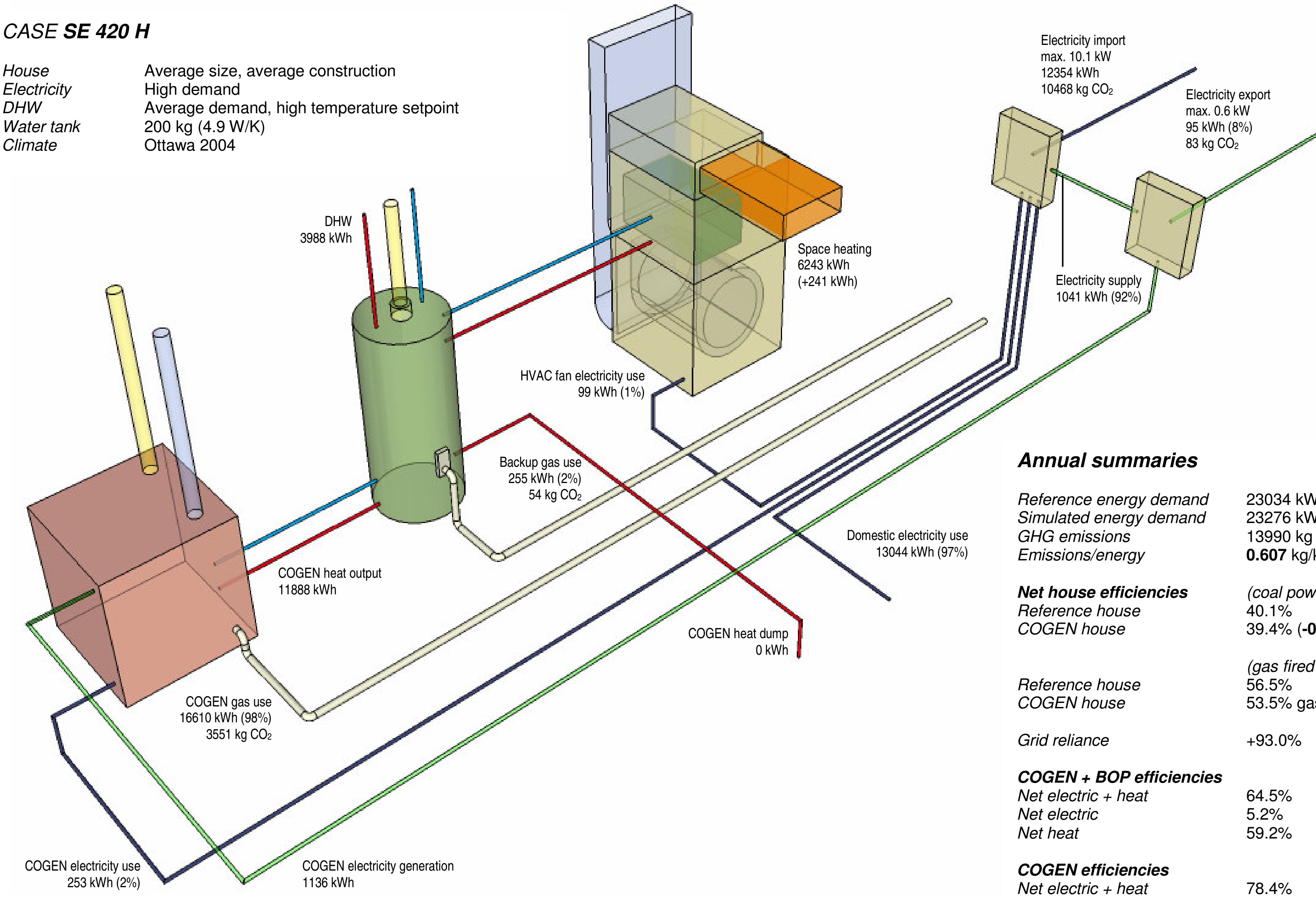
Reference energy demand	17949 kWh
Simulated energy demand	18309 kWh (**+2.0%**)
GHG emissions	7781 kg CO_2 (**+1.7%**)
Emissions/energy	**0.434** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	54.4%
COGEN house	52.6% (**-1.8%-p.**)
	(gas fired grid)
Reference house	67.4%
COGEN house	61.2% gas (**-6.2%-p.**)
Grid reliance	+76.0%
COGEN + BOP efficiencies	
Net electric + heat	67.5%
Net electric	5.5%
Net heat	62.0%
COGEN efficiencies	
Net electric + heat	79.2%
Net electric	7.1%
Gross heat	72.1%
Net heat	72.1%
COGEN heat dump/output	0.0%



CASE SE 410 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

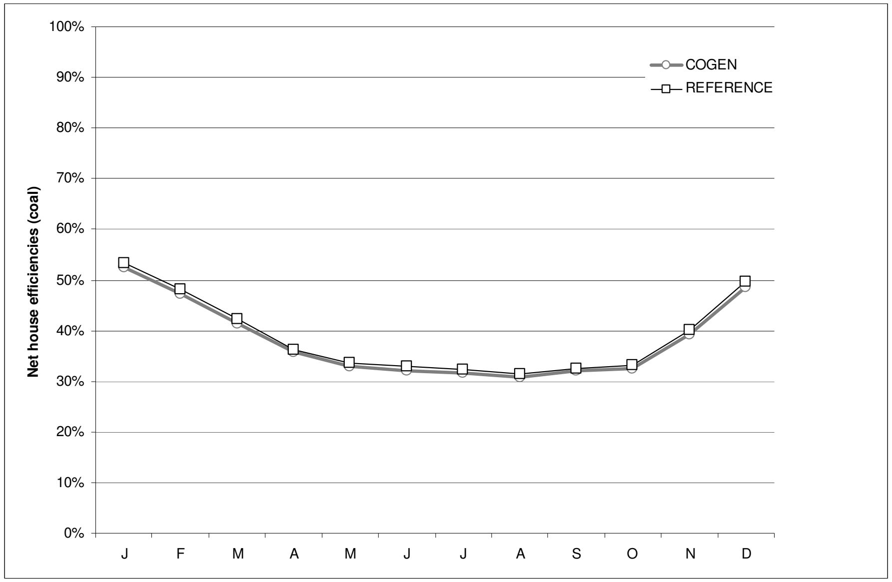
CASE ***SE 420 H***

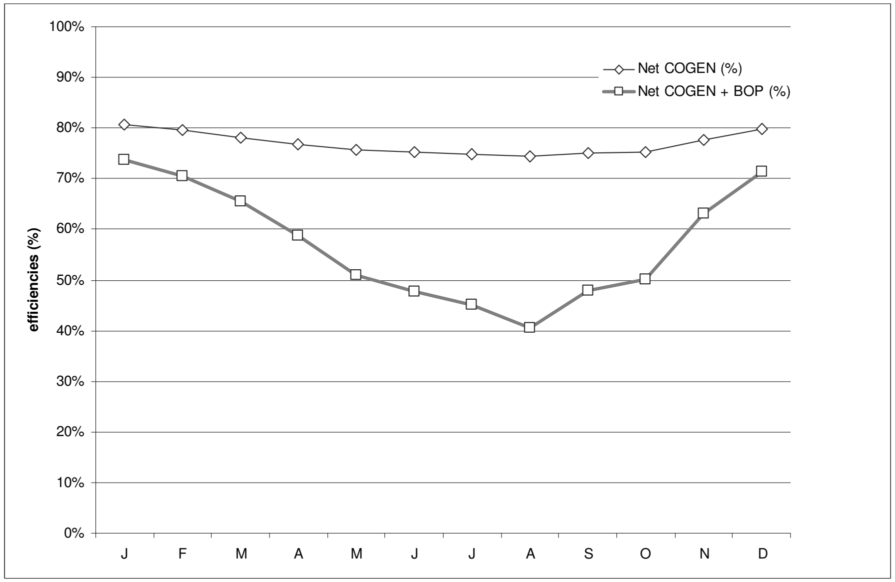
House	Average size, average construction
Electricity	High demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004

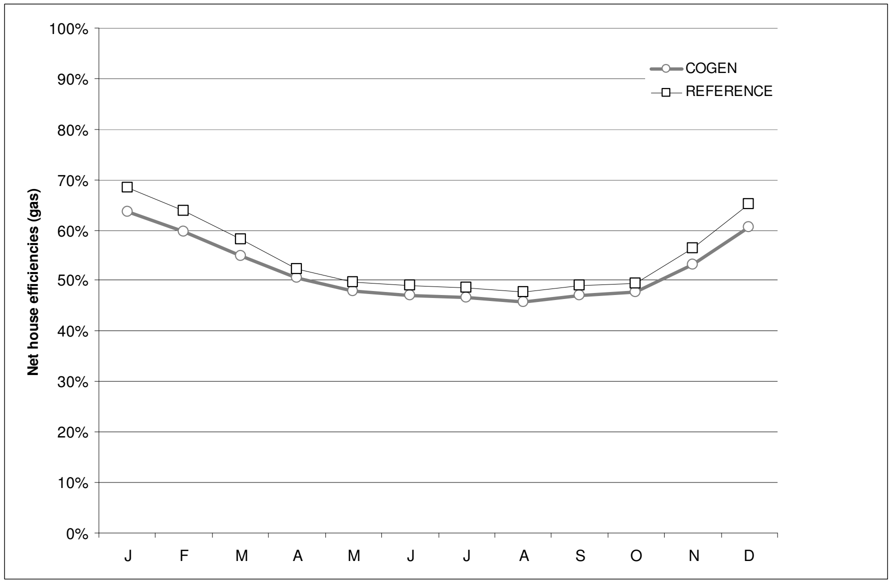


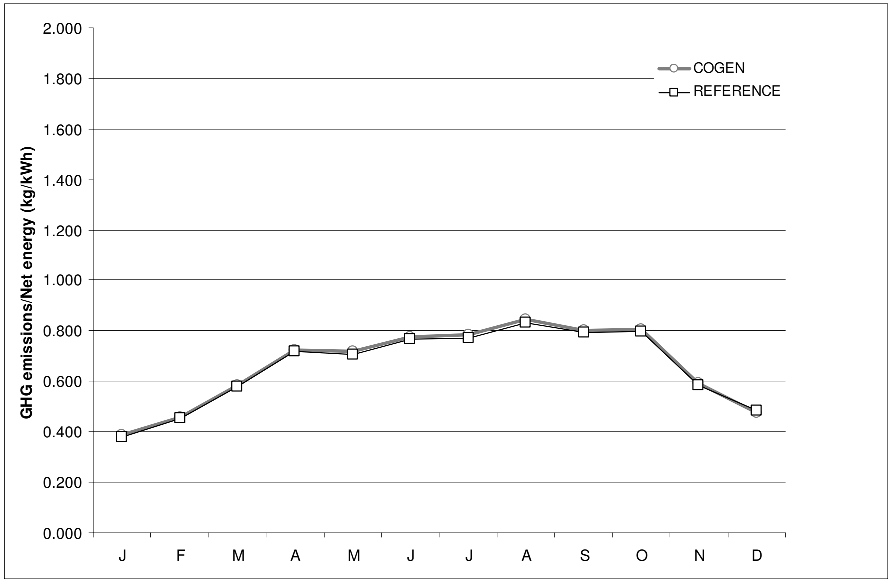
Annual summaries

Reference energy demand	23034 kWh
Simulated energy demand	23276 kWh (**+1.0%**)
GHG emissions	13990 kg CO_2 (**+1.1%**)
Emissions/energy	**0.607** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	40.1%
COGEN house	39.4% (**-0.7%-p.**)
	(gas fired grid)
Reference house	56.5%
COGEN house	53.5% gas (**-3.0%-p.**)
Grid reliance	+93.0%
COGEN + BOP efficiencies	
Net electric + heat	64.5%
Net electric	5.2%
Net heat	59.2%
COGEN efficiencies	
Net electric + heat	78.4%
Net electric	6.8%
Gross heat	71.6%
Net heat	71.6%
COGEN heat dump/output	0.0%







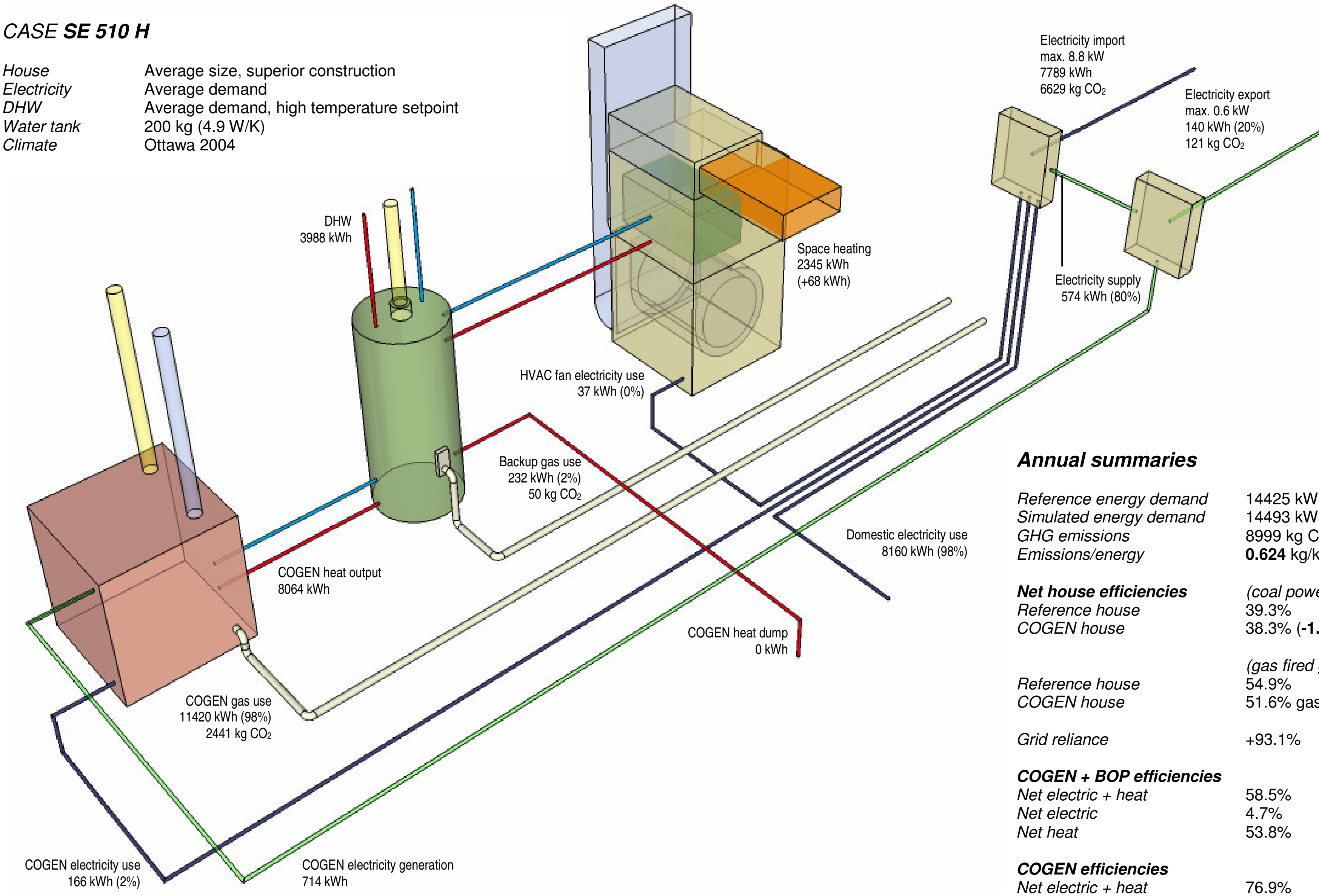


CASE SE 420 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

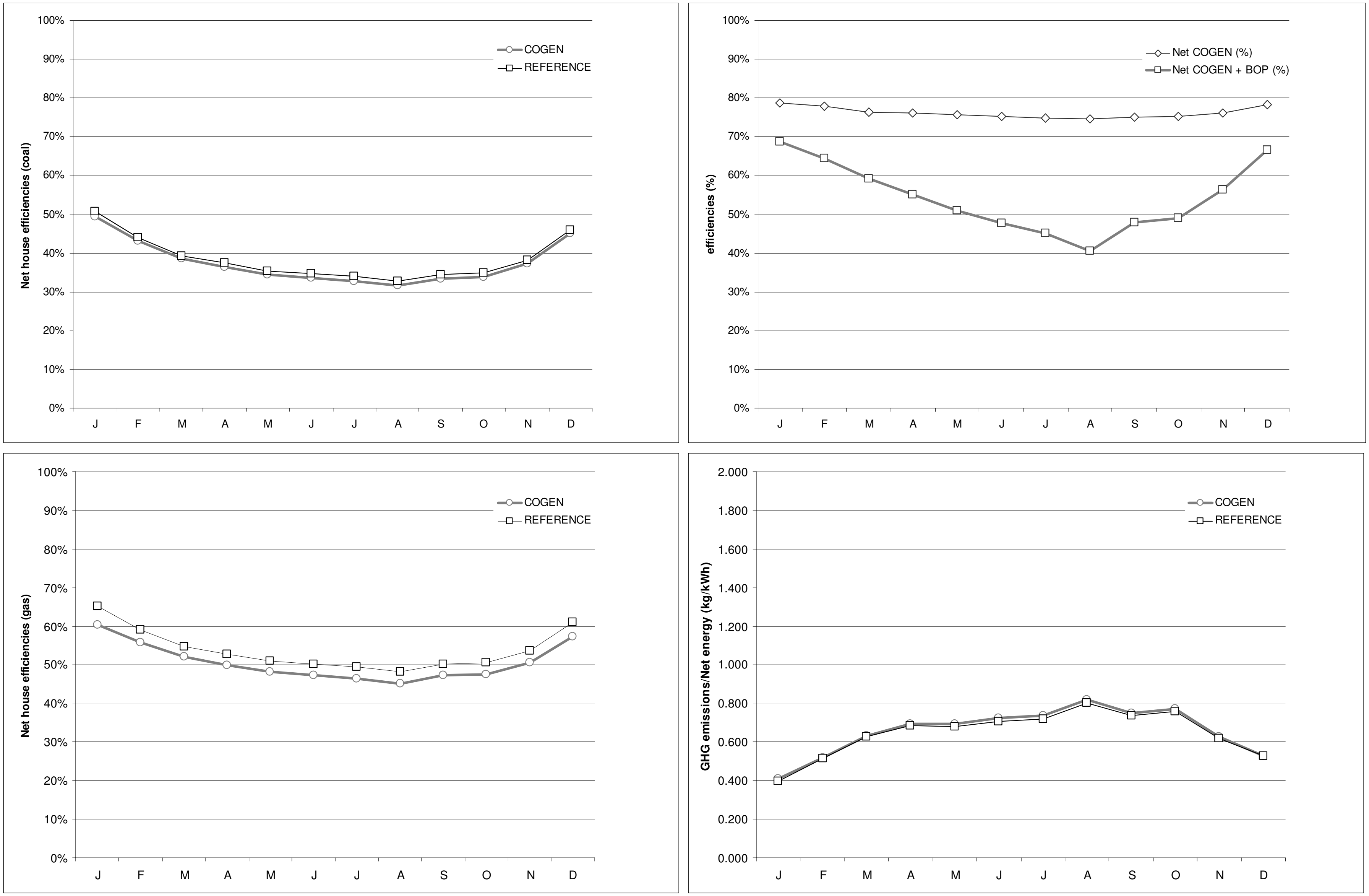
CASE ***SE 510 H***

House	Average size, superior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

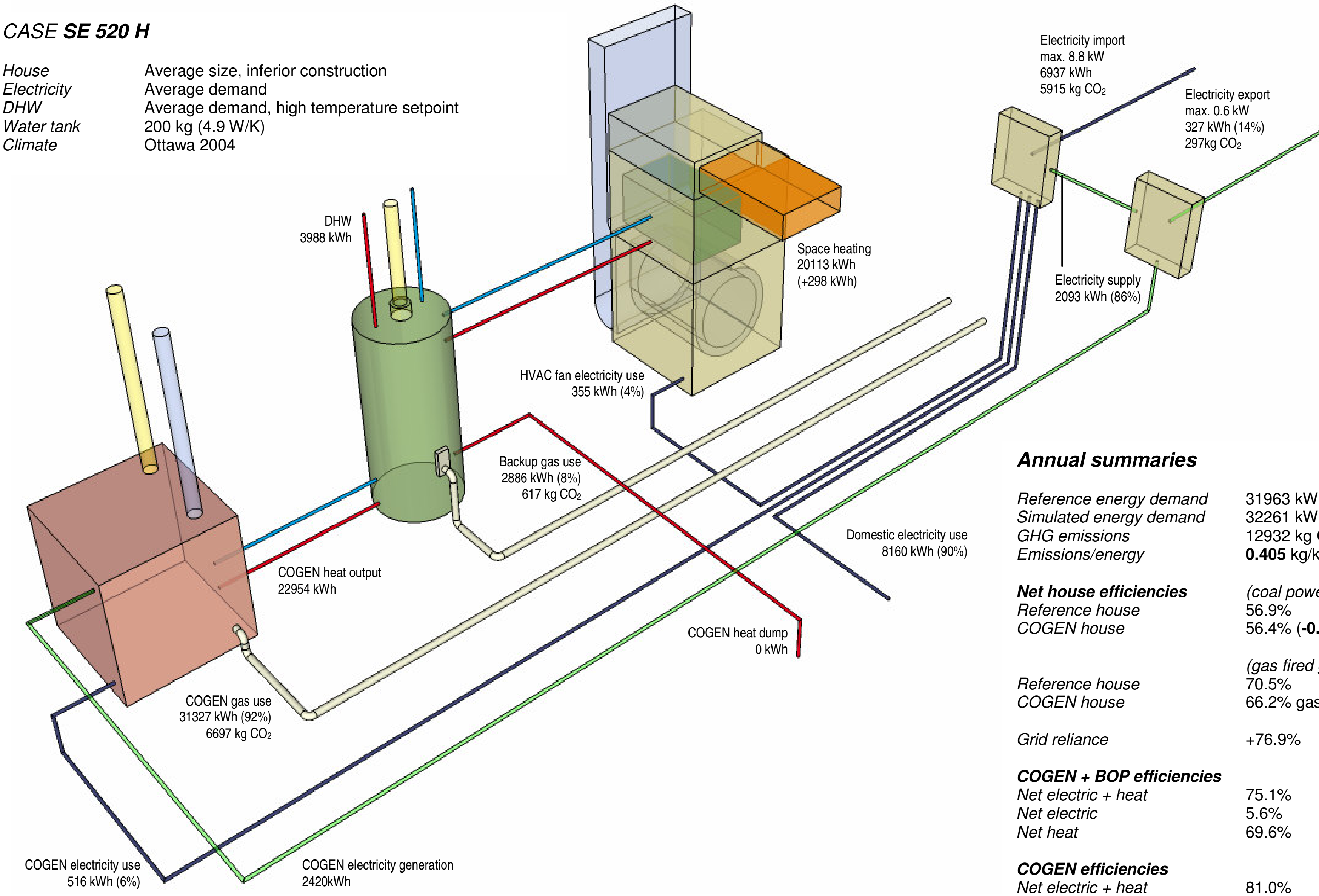
Reference energy demand	14425 kWh
Simulated energy demand	14493 kWh (**+0.5%**)
GHG emissions	8999 kg CO_2 (**+1.6%**)
Emissions/energy	**0.624** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	39.3%
COGEN house	38.3% (**-1.0%-p.**)
	(gas fired grid)
Reference house	54.9%
COGEN house	51.6% gas (**-3.3%-p.**)
Grid reliance	+93.1%
COGEN + BOP efficiencies	
Net electric + heat	58.5%
Net electric	4.7%
Net heat	53.8%
COGEN efficiencies	
Net electric + heat	76.9%
Net electric	6.2%
Gross heat	70.6%
Net heat	70.6%
COGEN heat dump/output	0.0%



CASE SE 510 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

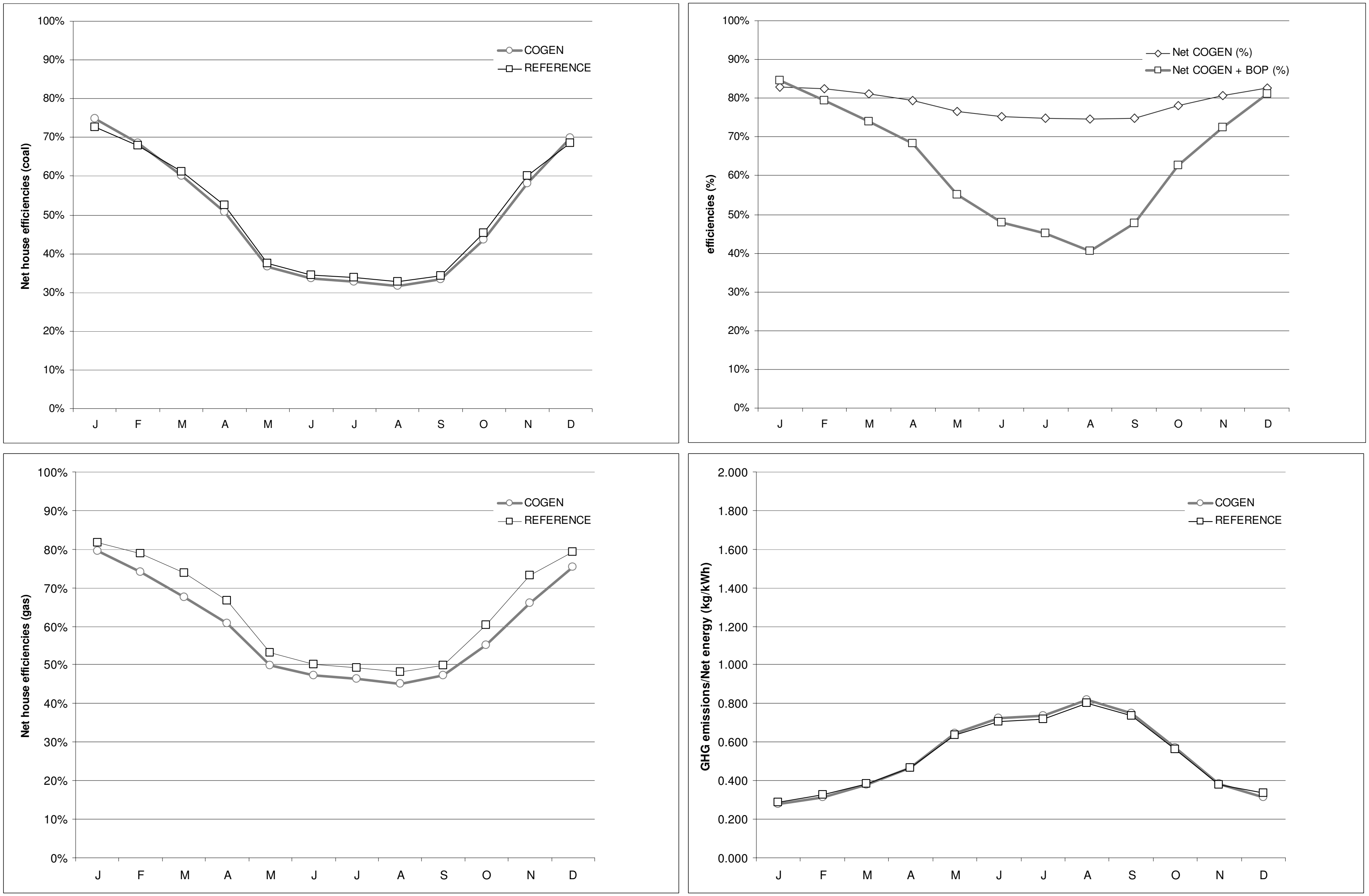
CASE ***SE 520 H***

House	Average size, inferior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	31963 kWh
Simulated energy demand	32261 kWh (**+0.9%**)
GHG emissions	12932 kg CO_2 (**-1.0%**)
Emissions/energy	**0.405** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	56.9%
COGEN house	56.4% (**-0.5%-p.**)
	(gas fired grid)
Reference house	70.5%
COGEN house	66.2% gas (**-4.4%-p.**)
Grid reliance	+76.9%
COGEN + BOP efficiencies	
Net electric + heat	75.1%
Net electric	5.6%
Net heat	69.6%
COGEN efficiencies	
Net electric + heat	81.0%
Net electric	7.7%
Gross heat	73.3%
Net heat	73.3%
COGEN heat dump/output	0.0%

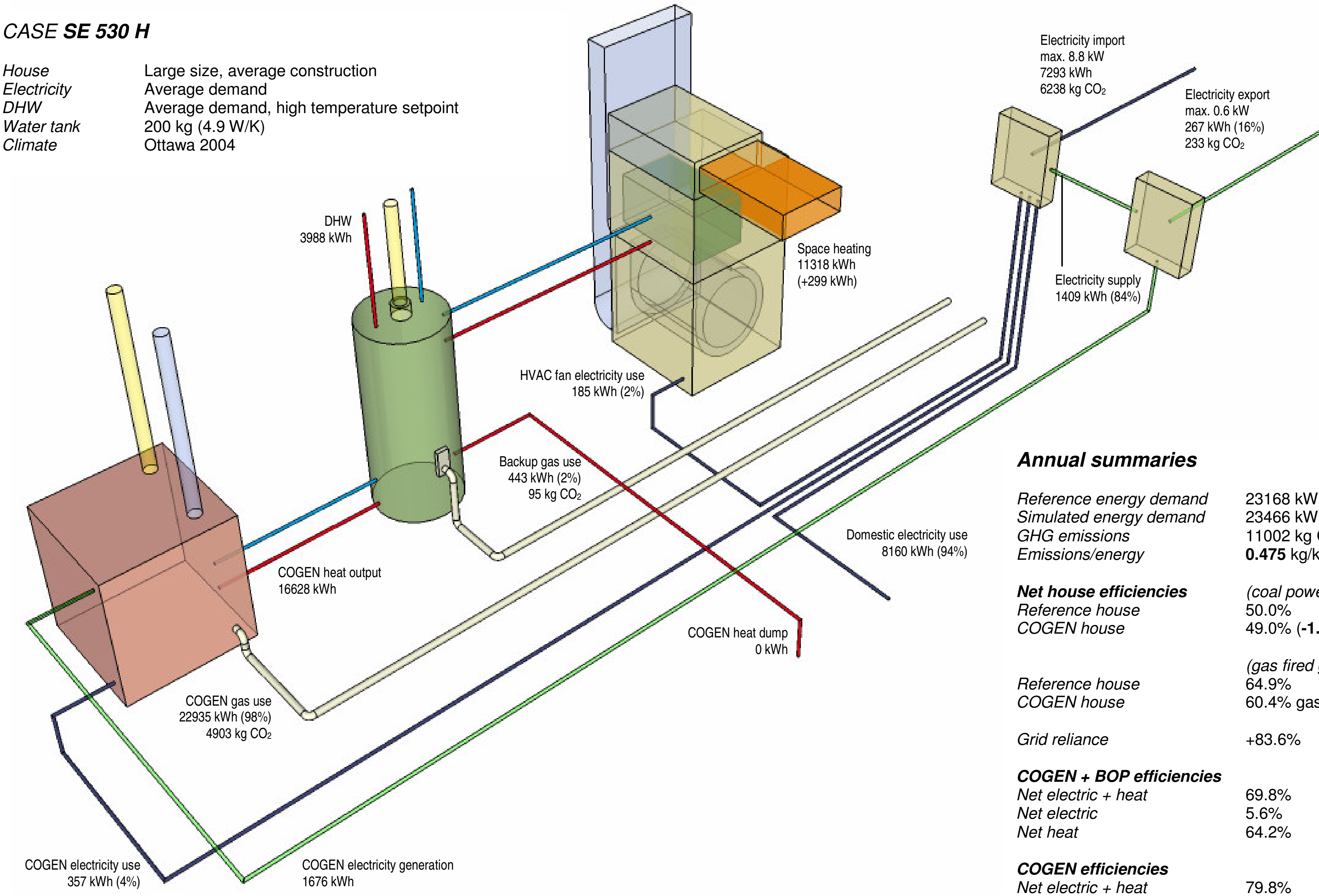


CASE SE 520 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

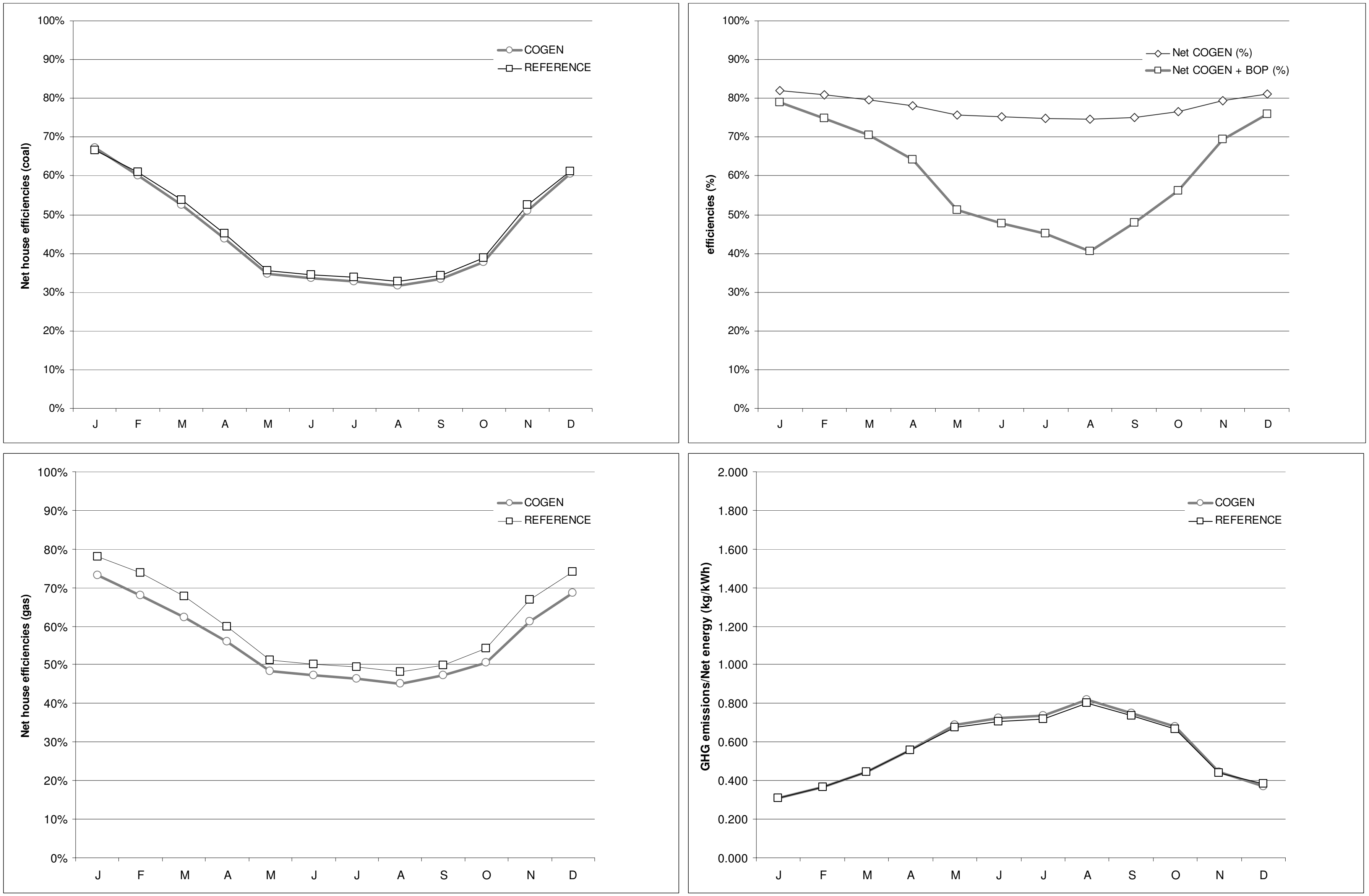
CASE ***SE 530 H***

House	Large size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

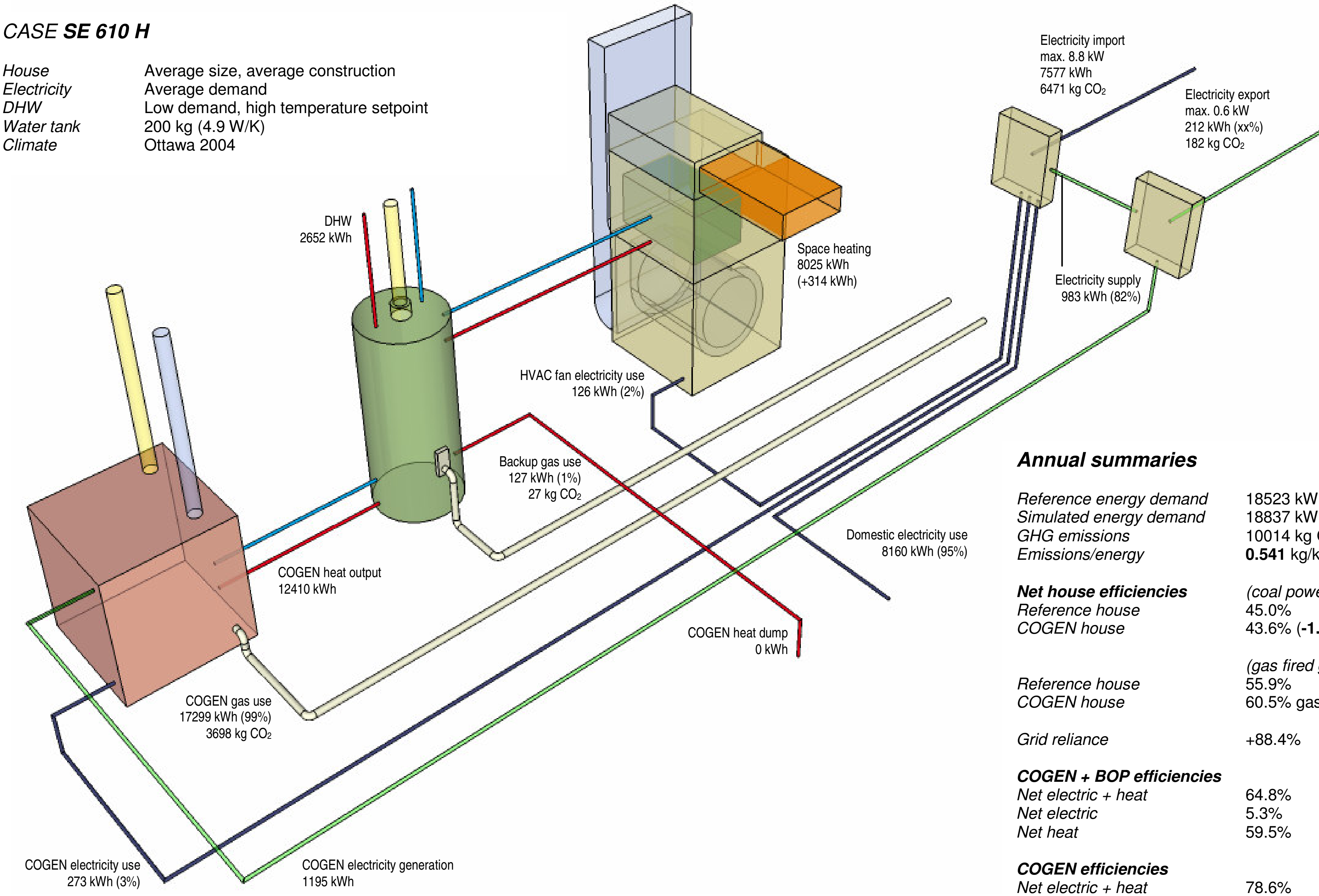
Reference energy demand	23168 kWh
Simulated energy demand	23466 kWh (**+1.3%**)
GHG emissions	11002 kg CO_2 (**+0.7%**)
Emissions/energy	**0.475** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	50.0%
COGEN house	49.0% (**-1.0%-p.**)
	(gas fired grid)
Reference house	64.9%
COGEN house	60.4% gas (**-4.5%-p.**)
Grid reliance	+83.6%
COGEN + BOP efficiencies	
Net electric + heat	69.8%
Net electric	5.6%
Net heat	64.2%
COGEN efficiencies	
Net electric + heat	79.8%
Net electric	7.3%
Gross heat	72.5%
Net heat	72.5%
COGEN heat dump/output	0.0%



CASE SE 530 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

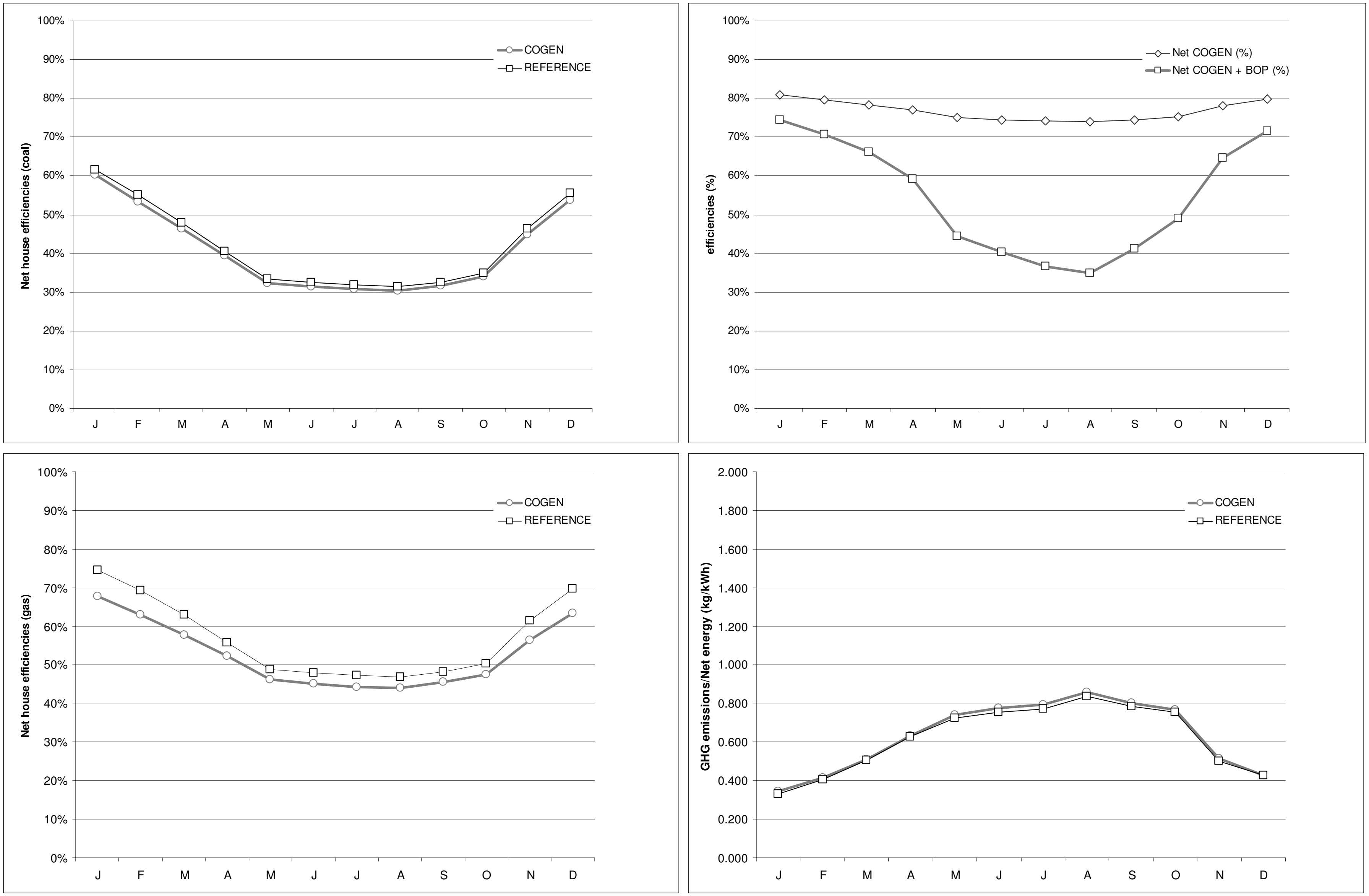
CASE ***SE 610 H***

House	Average size, average construction
Electricity	Average demand
DHW	Low demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	18523 kWh
Simulated energy demand	18837 kWh (**+1.7%**)
GHG emissions	10014 kg CO_2 (**+1.9%**)
Emissions/energy	**0.541** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	45.0%
COGEN house	43.6% (**-1.3%-p.**)
	(gas fired grid)
Reference house	55.9%
COGEN house	60.5% gas (**-4.5%-p.**)
Grid reliance	+88.4%
COGEN + BOP efficiencies	
Net electric + heat	64.8%
Net electric	5.3%
Net heat	59.5%
COGEN efficiencies	
Net electric + heat	78.6%
Net electric	6.9%
Gross heat	71.7%
Net heat	71.7%
COGEN heat dump/output	0.0%

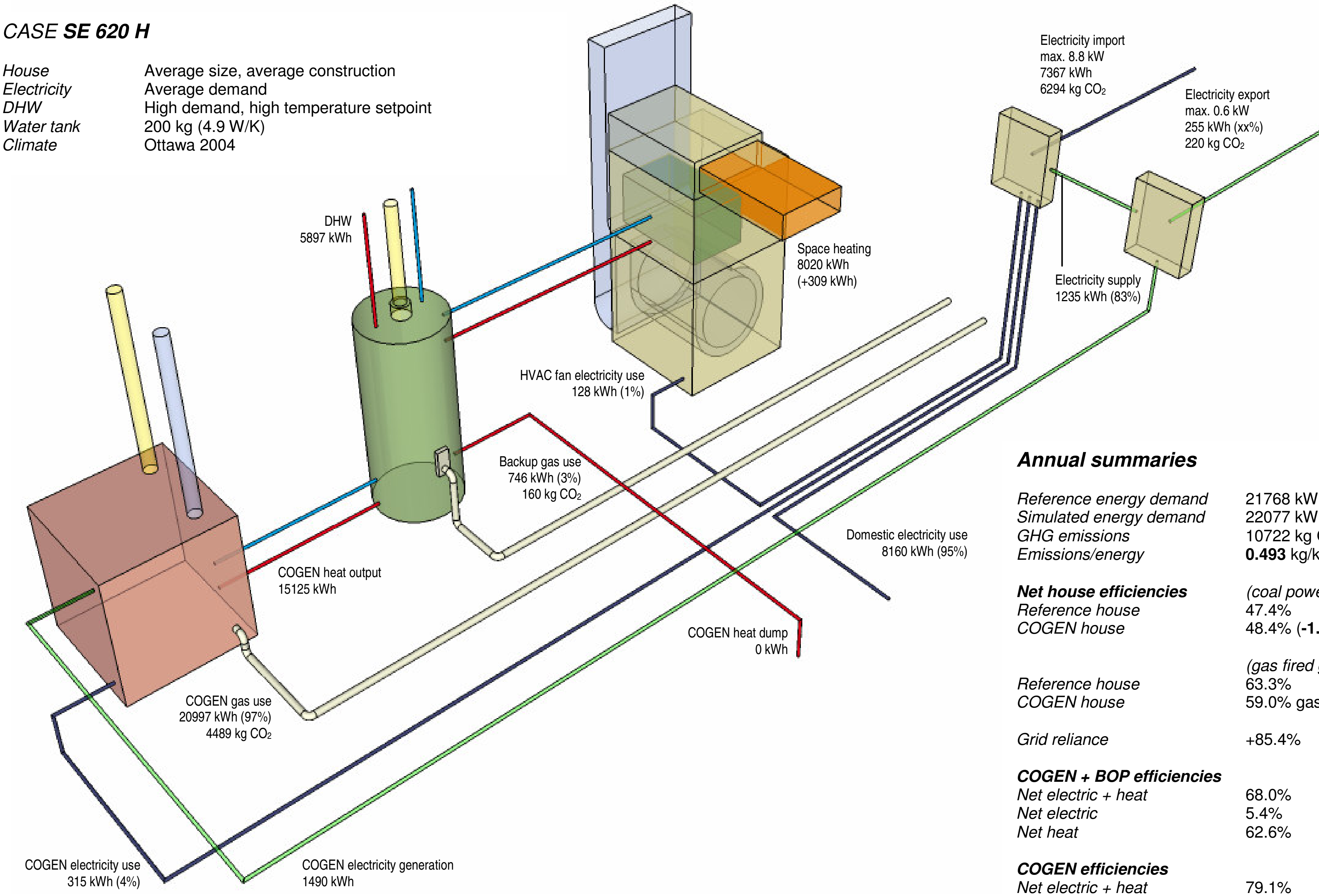


CASE SE 610 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

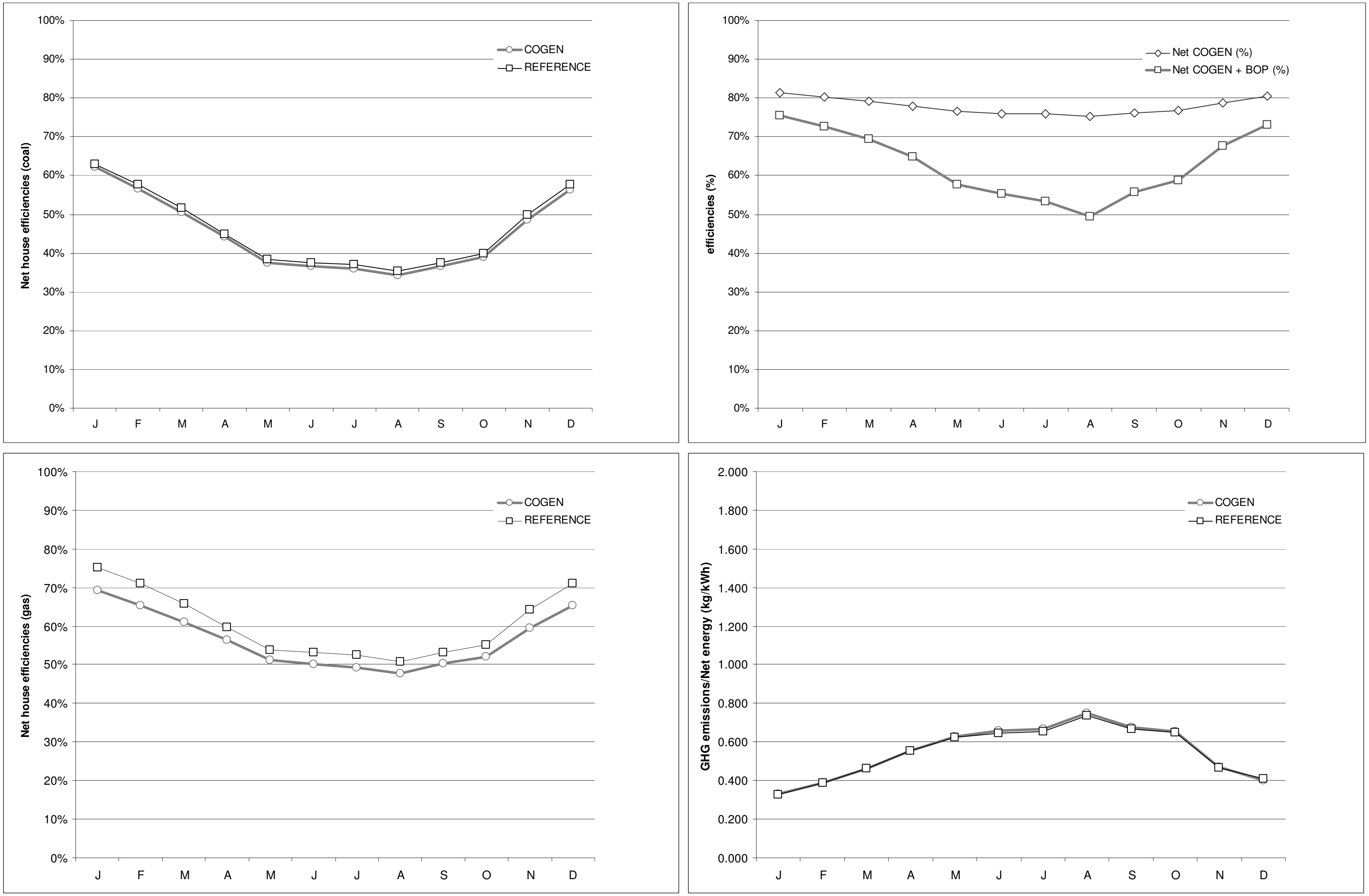
CASE ***SE 620 H***

House	Average size, average construction
Electricity	Average demand
DHW	High demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

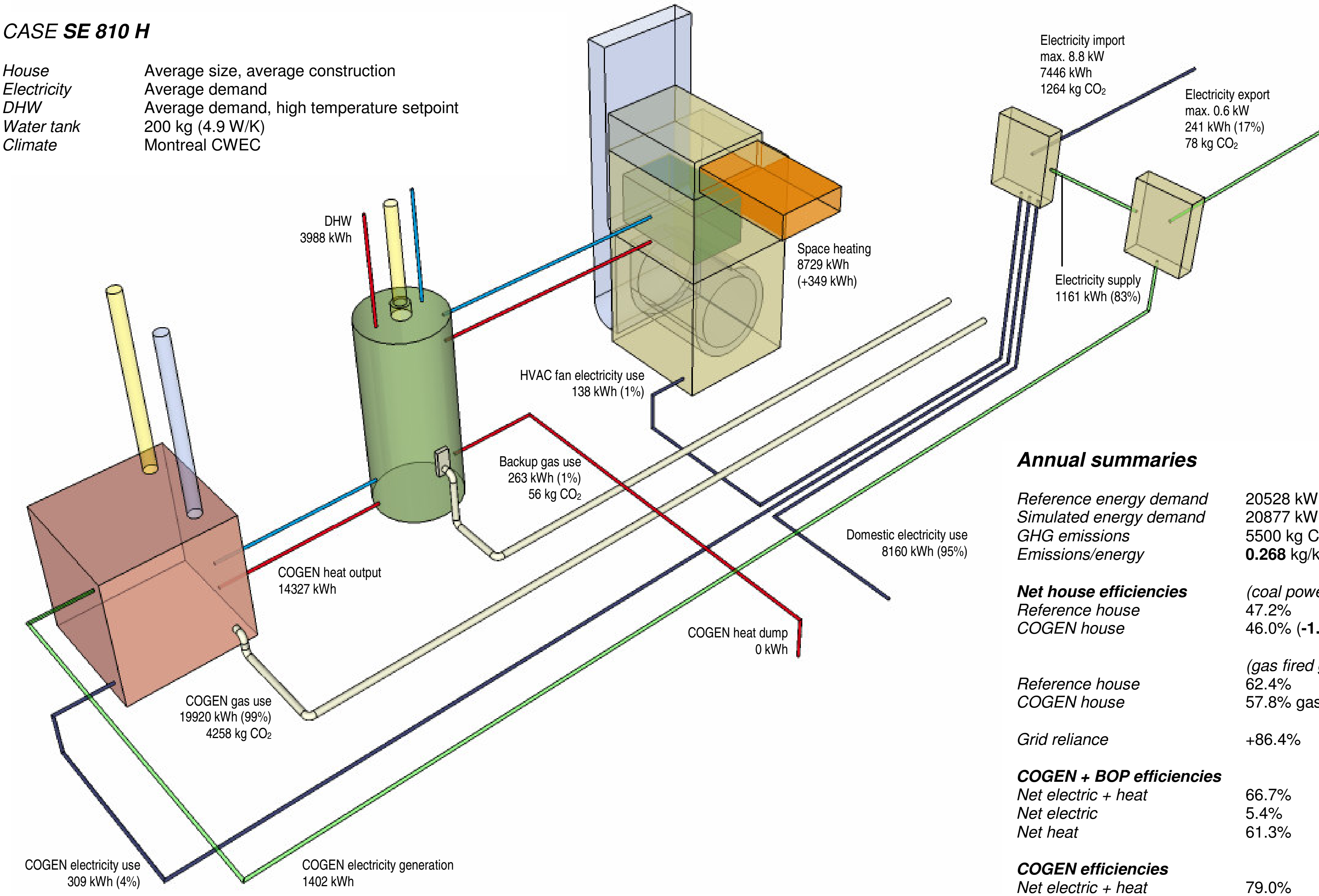
Reference energy demand	21768 kWh
Simulated energy demand	22077 kWh (**+1.4%**)
GHG emissions	10722 kg CO_2 (**+0.9%**)
Emissions/energy	**0.493** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.4%
COGEN house	48.4% (**-1.0%-p.**)
	(gas fired grid)
Reference house	63.3%
COGEN house	59.0% gas (**-4.3%-p.**)
Grid reliance	+85.4%
COGEN + BOP efficiencies	
Net electric + heat	68.0%
Net electric	5.4%
Net heat	62.6%
COGEN efficiencies	
Net electric + heat	79.1%
Net electric	7.1%
Gross heat	72.0%
Net heat	72.0%
COGEN heat dump/output	0.0%



CASE SE 620 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

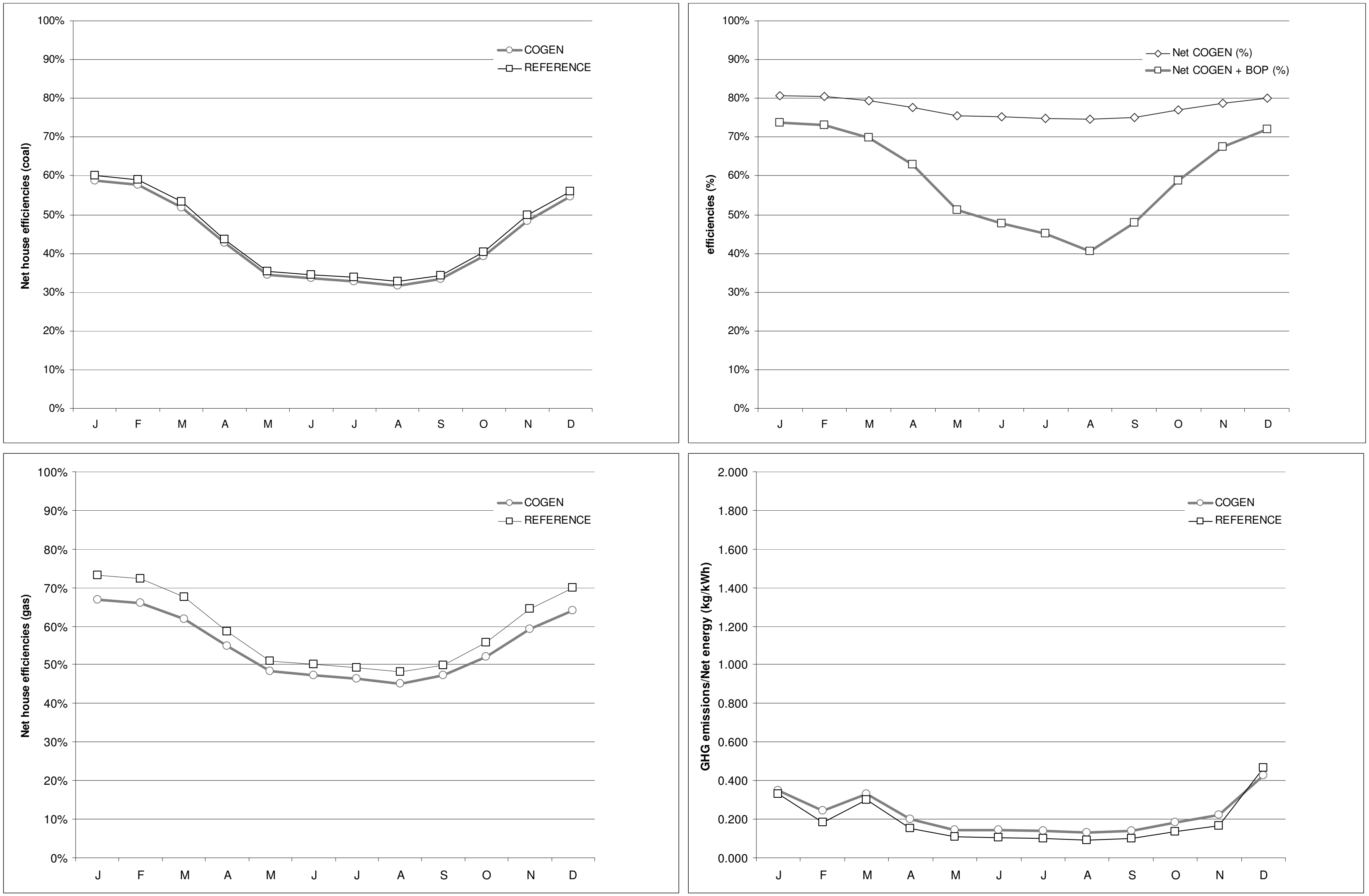
CASE ***SE 810 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Montreal CWEC



Annual summaries

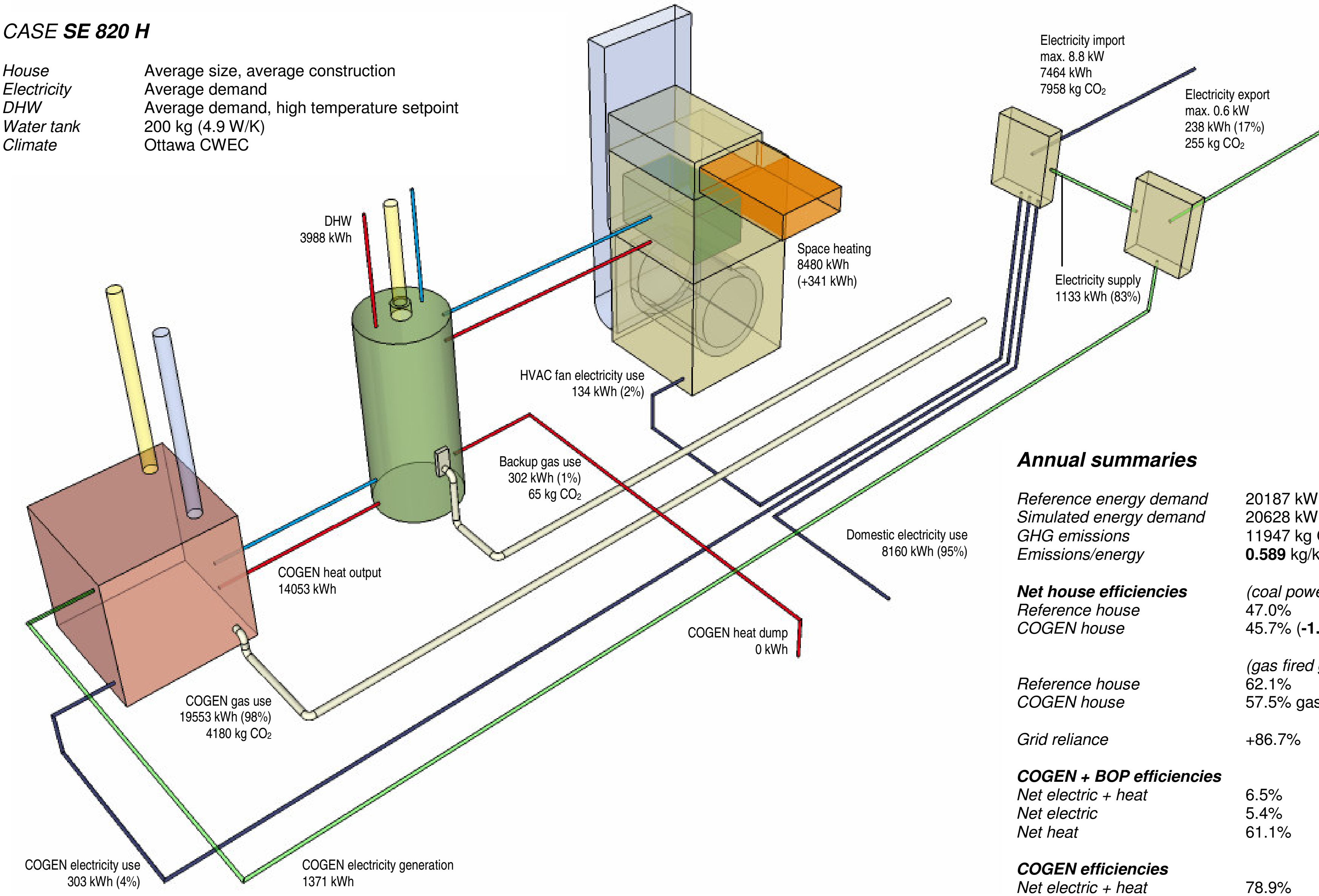
Reference energy demand	20528 kWh
Simulated energy demand	20877 kWh (**+1.7%**)
GHG emissions	5500 kg CO_2 (**+14.0%**)
Emissions/energy	**0.268** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.2%
COGEN house	46.0% (**-1.3%-p.**)
	(gas fired grid)
Reference house	62.4%
COGEN house	57.8% gas (**-4.6%-p.**)
Grid reliance	+86.4%
COGEN + BOP efficiencies	
Net electric + heat	66.7%
Net electric	5.4%
Net heat	61.3%
COGEN efficiencies	
Net electric + heat	79.0%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 810 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

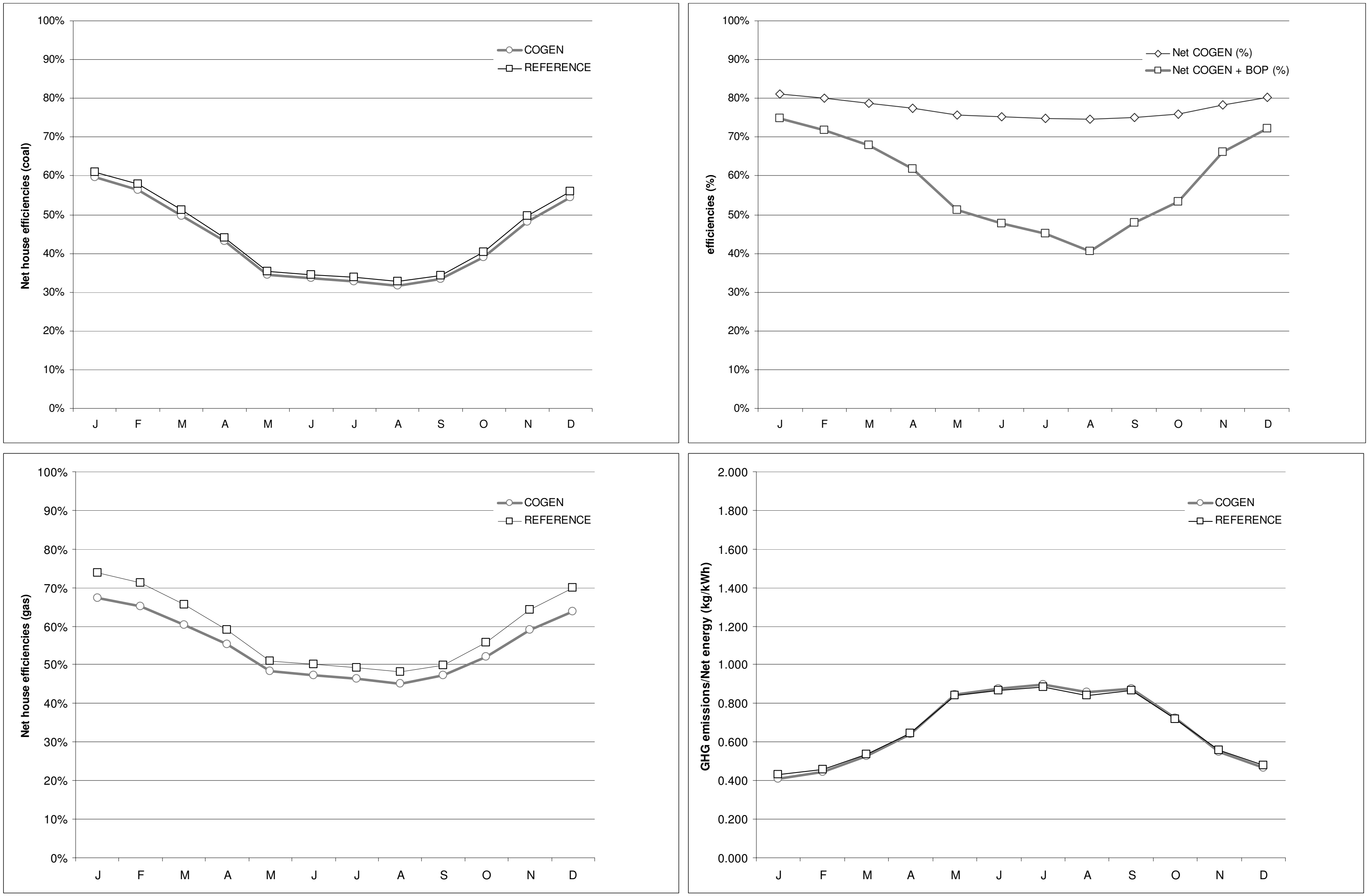
CASE ***SE 820 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa CWEC



Annual summaries

Reference energy demand	20187 kWh
Simulated energy demand	20628 kWh (**+1.7%**)
GHG emissions	11947 kg CO_2 (**-1.1%**)
Emissions/energy	**0.589** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	45.7% (**-1.3%-p.**)
	(gas fired grid)
Reference house	62.1%
COGEN house	57.5% gas (**-4.6%-p.**)
Grid reliance	+86.7%
COGEN + BOP efficiencies	
Net electric + heat	6.5%
Net electric	5.4%
Net heat	61.1%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%

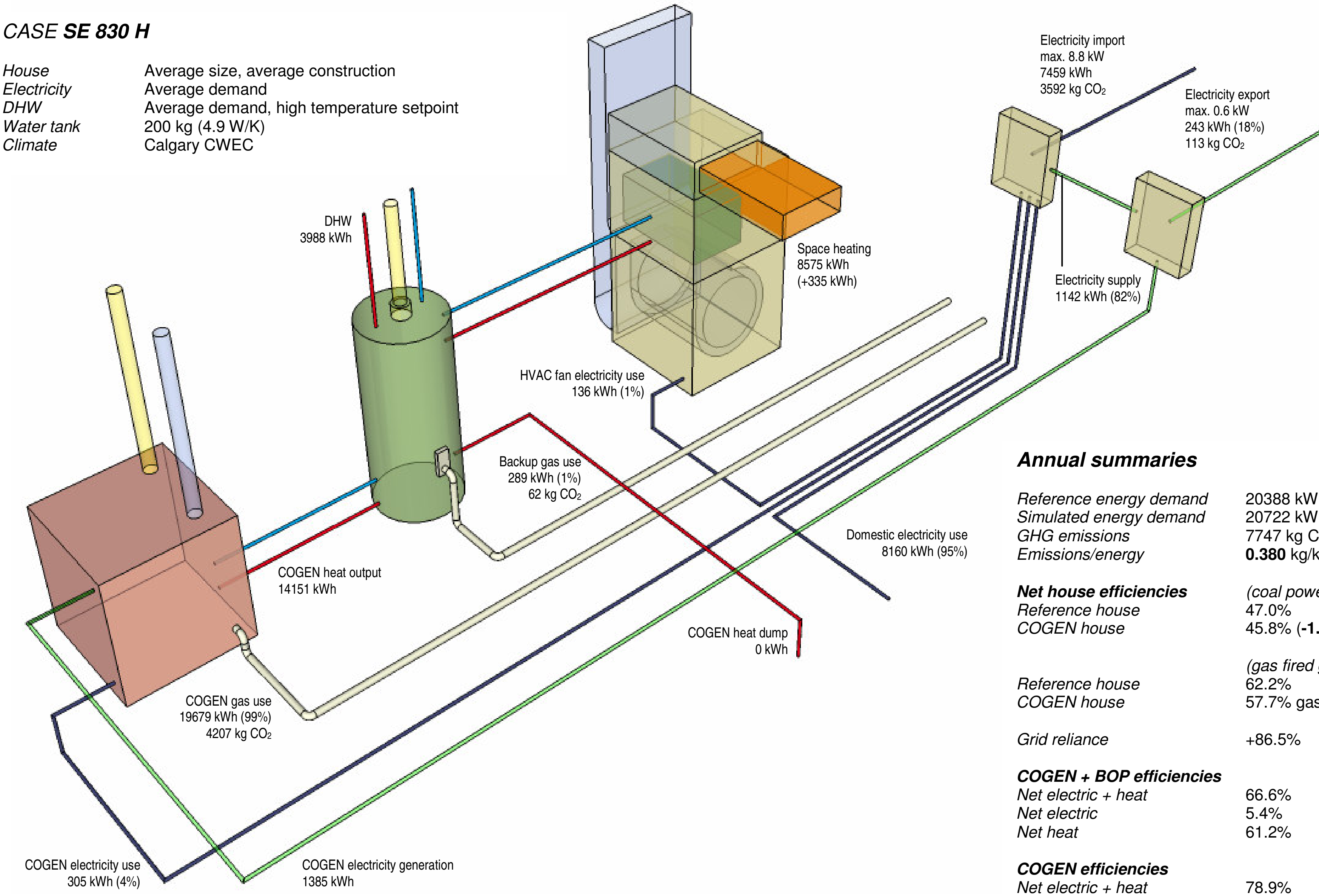


CASE SE 820 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

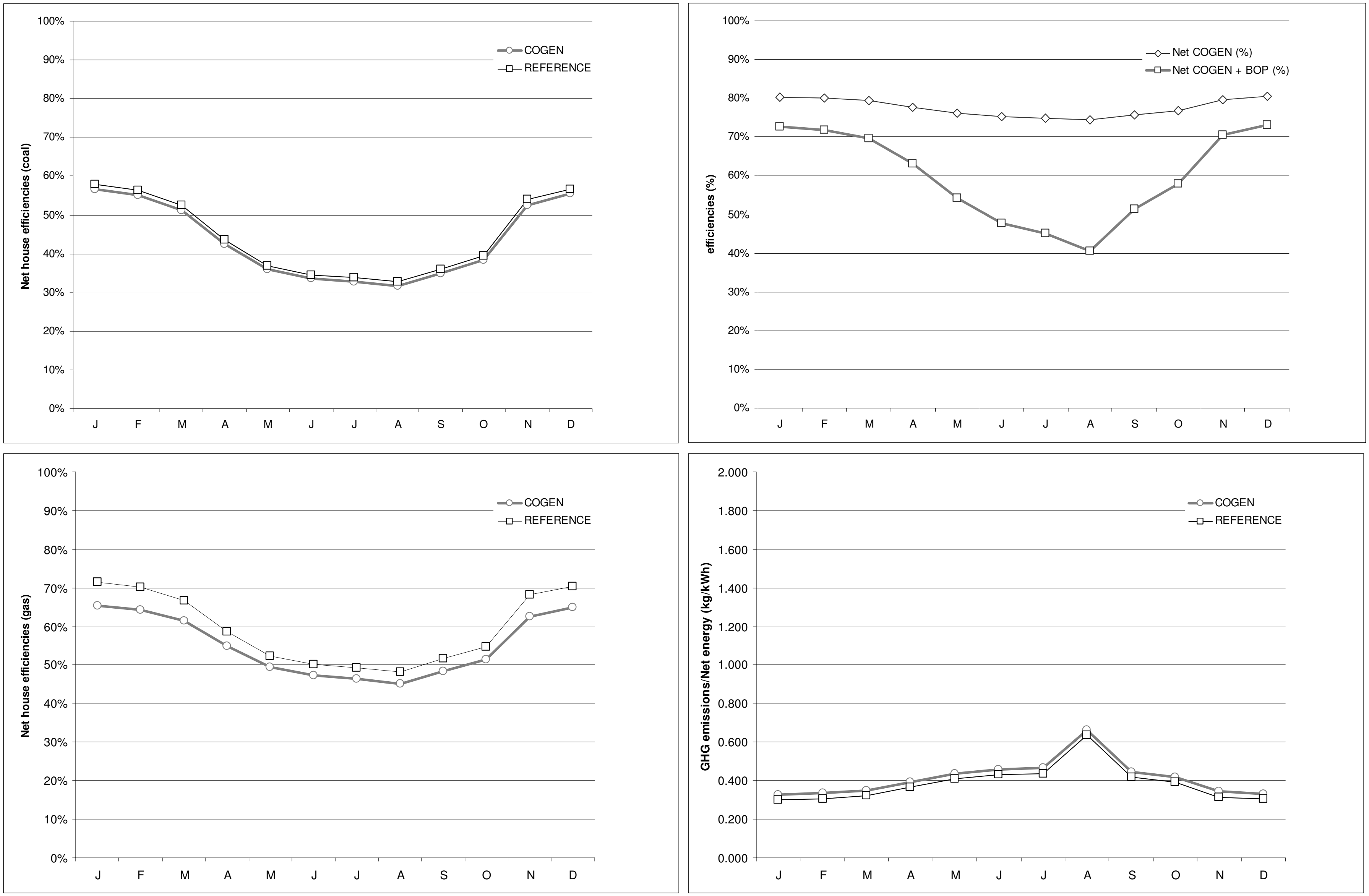
CASE ***SE 830 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Calgary CWEC



Annual summaries

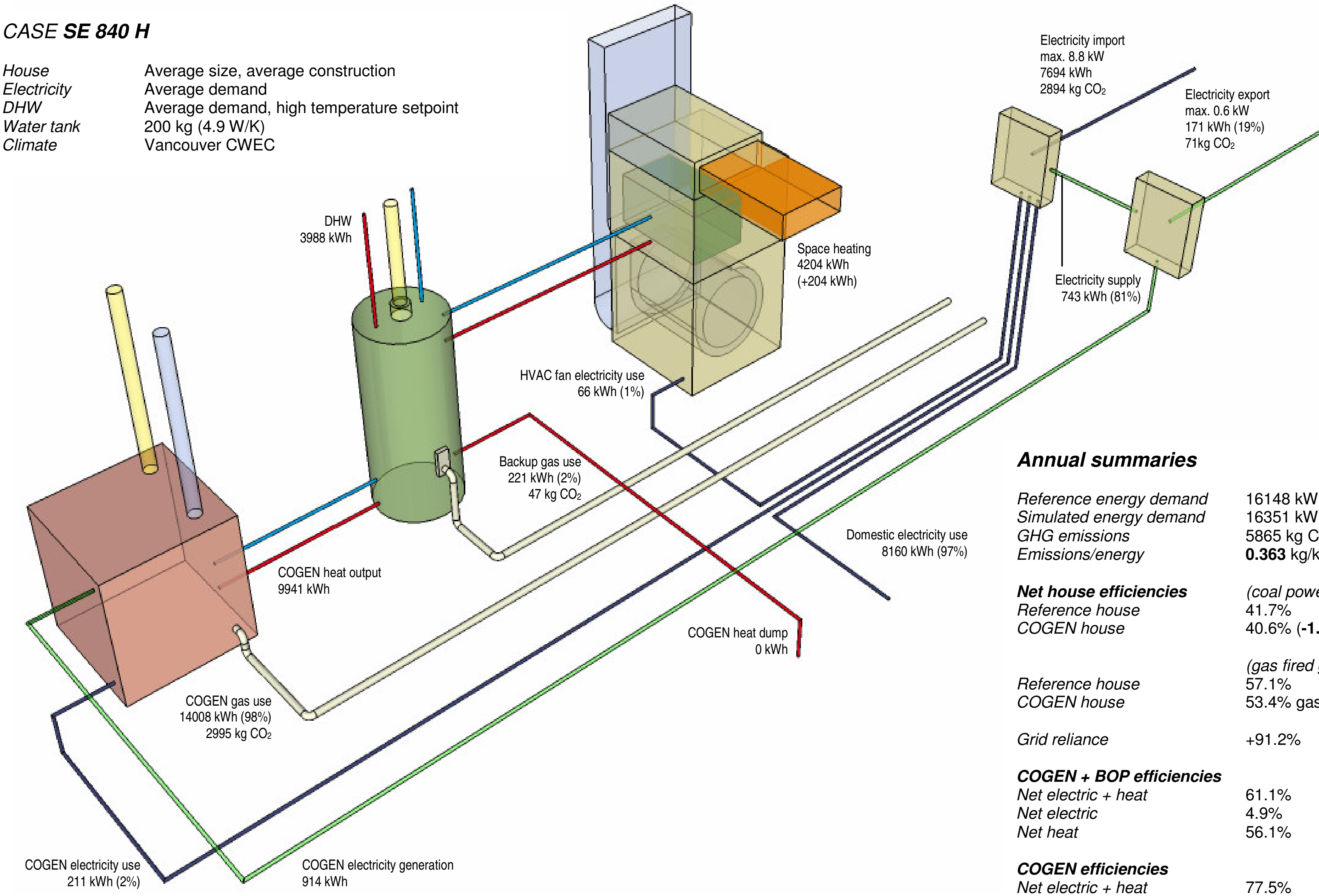
Reference energy demand	20388 kWh
Simulated energy demand	20722 kWh (**+1.6%**)
GHG emissions	7747 kg CO_2 (**+7.4%**)
Emissions/energy	**0.380** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	45.8% (**-1.2%-p.**)
	(gas fired grid)
Reference house	62.2%
COGEN house	57.7% gas (**-4.5%-p.**)
Grid reliance	+86.5%
COGEN + BOP efficiencies	
Net electric + heat	66.6%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 830 H *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

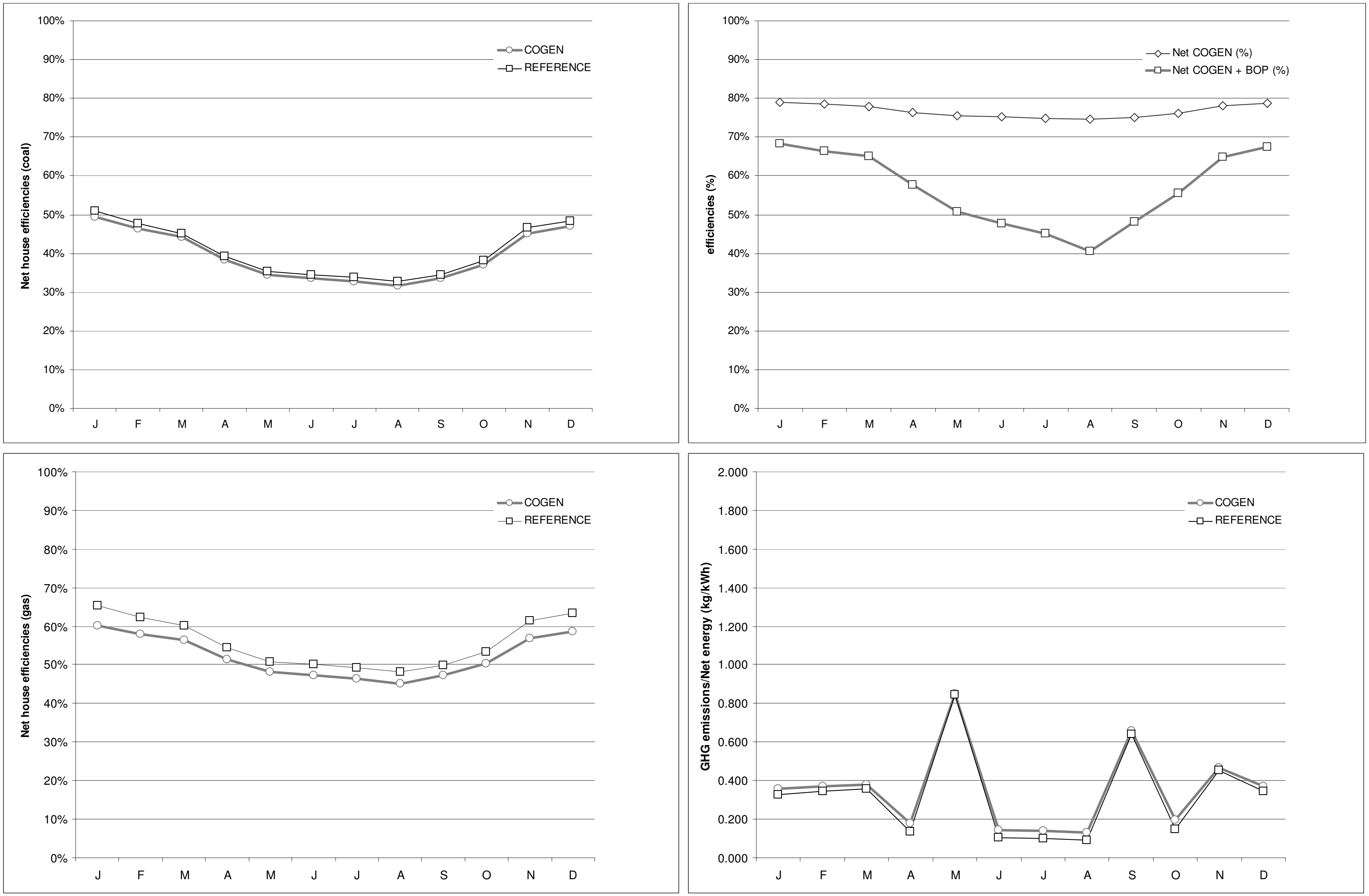
CASE ***SE 840 H***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Vancouver CWEC



Annual summaries

Reference energy demand	16148 kWh
Simulated energy demand	16351 kWh (**+1.3%**)
GHG emissions	5865 kg CO_2 (**+8.1%**)
Emissions/energy	**0.363** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	41.7%
COGEN house	40.6% (**-1.1%-p.**)
	(gas fired grid)
Reference house	57.1%
COGEN house	53.4% gas (**-3.7%-p.**)
Grid reliance	+91.2%
COGEN + BOP efficiencies	
Net electric + heat	61.1%
Net electric	4.9%
Net heat	56.1%
COGEN efficiencies	
Net electric + heat	77.5%
Net electric	6.5%
Gross heat	71.0%
Net heat	71.0%
COGEN heat dump/output	0.0%

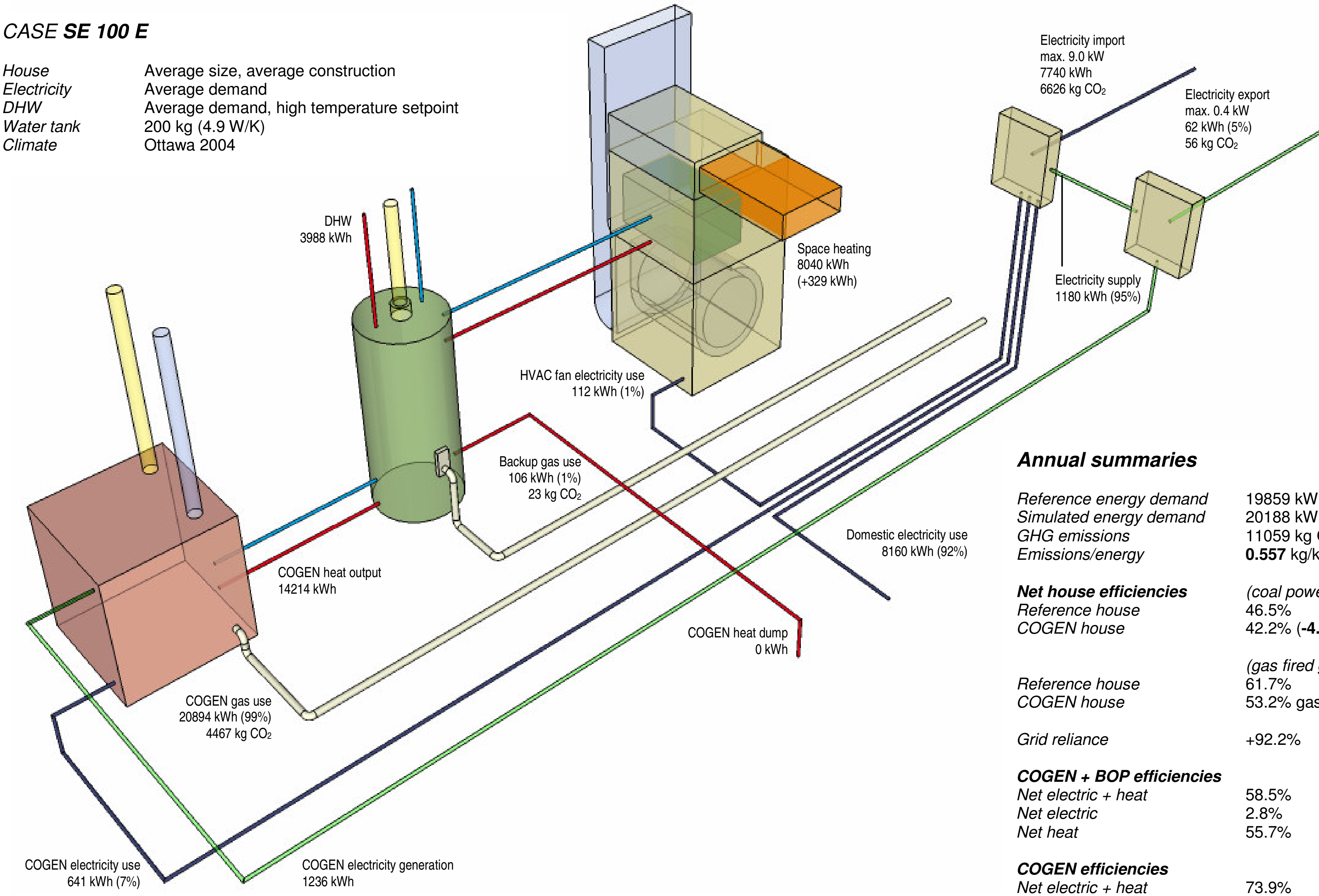


CASE SE 840 H

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

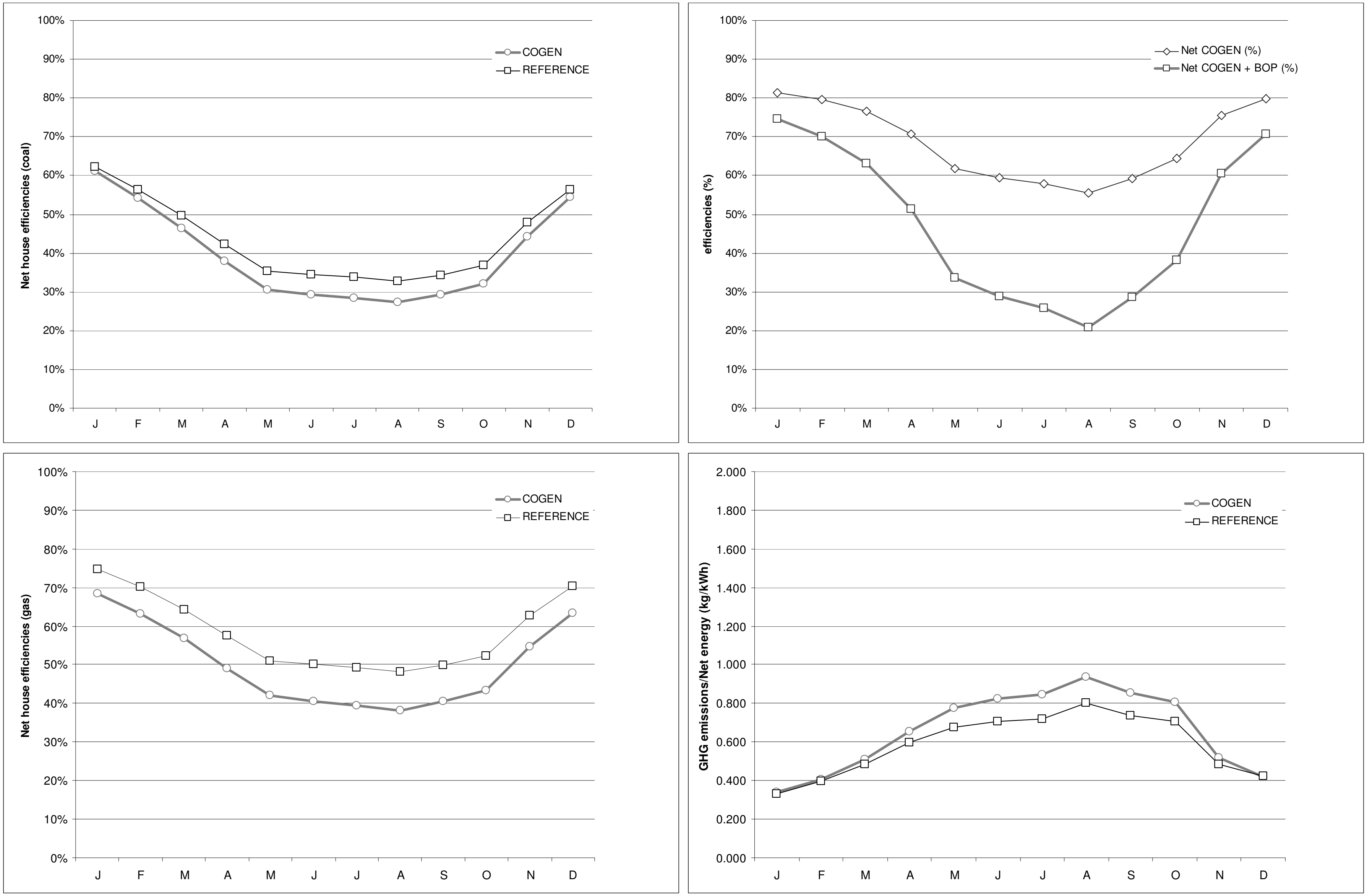
CASE ***SE 100 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

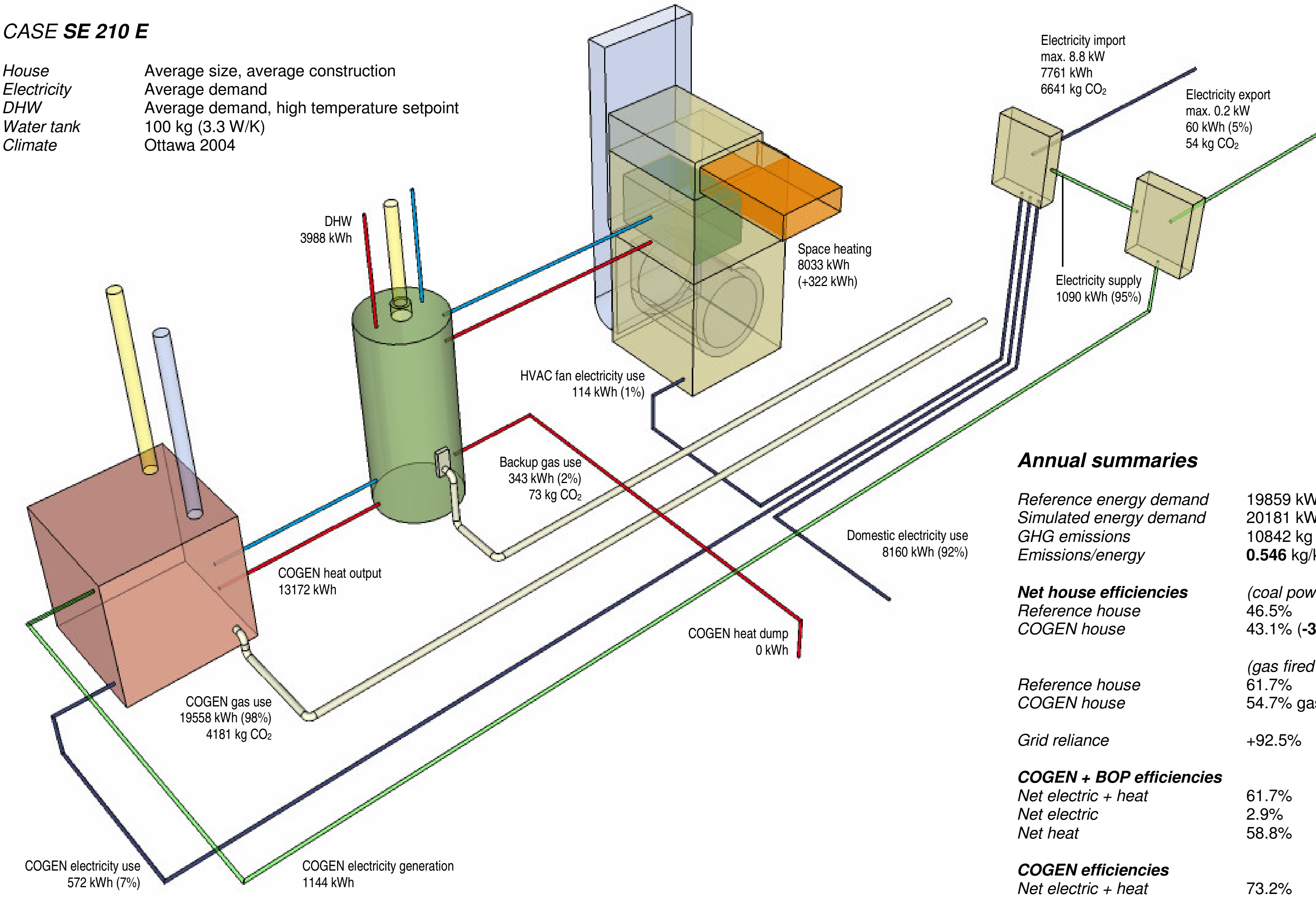
Reference energy demand	19859 kWh
Simulated energy demand	20188 kWh (**+1.7%**)
GHG emissions	11059 kg CO_2 (**+8.9%**)
Emissions/energy	**0.557** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	42.2% (**-4.3%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	53.2% gas (**-8.5%-p.**)
Grid reliance	+92.2%
COGEN + BOP efficiencies	
Net electric + heat	58.5%
Net electric	2.8%
Net heat	55.7%
COGEN efficiencies	
Net electric + heat	73.9%
Net electric	5.9%
Gross heat	68.0%
Net heat	68.0%
COGEN heat dump/output	0.0%



CASE SE 100 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

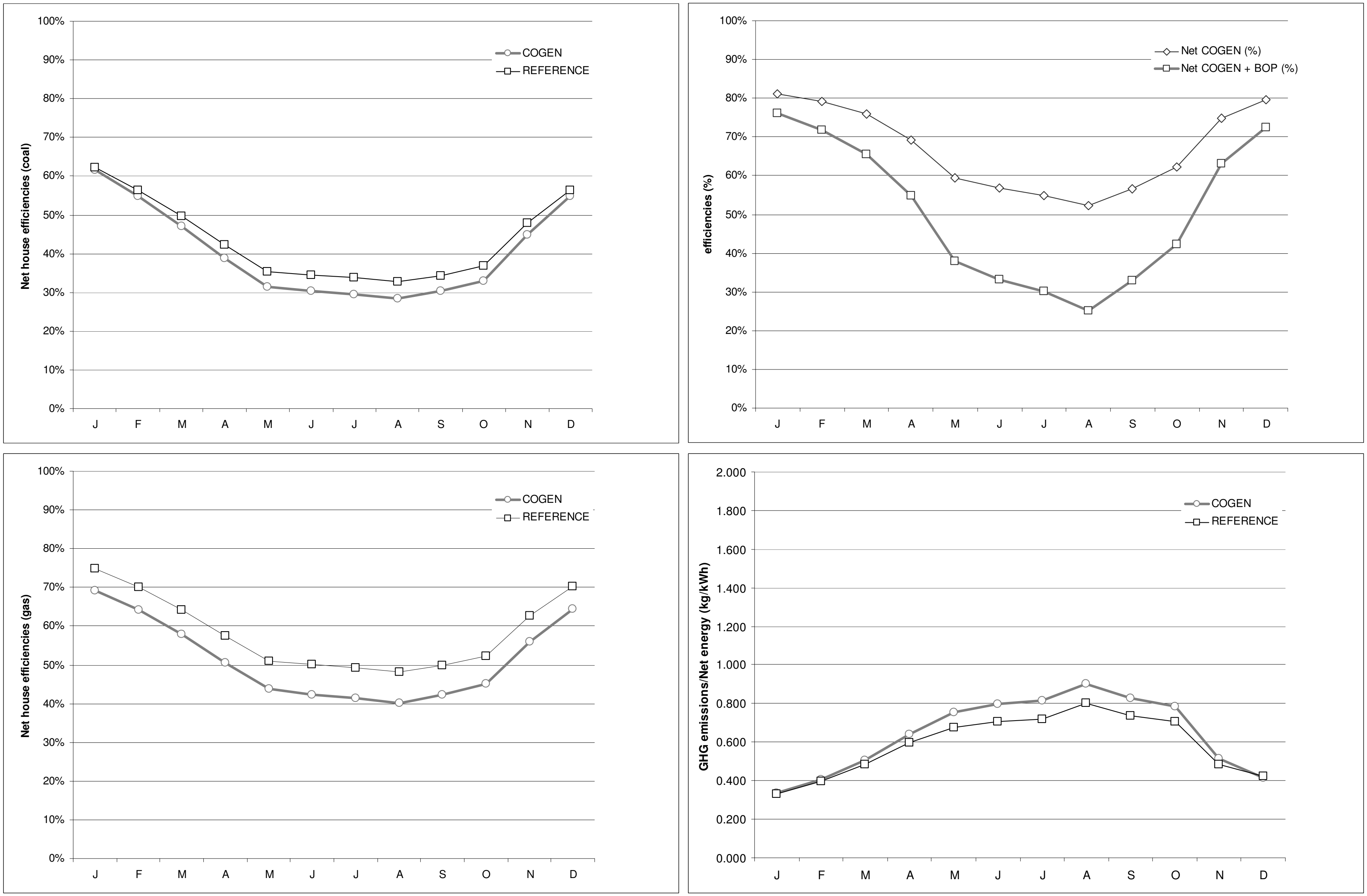
CASE ***SE 210 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	100 kg (3.3 W/K)
Climate	Ottawa 2004



Annual summaries

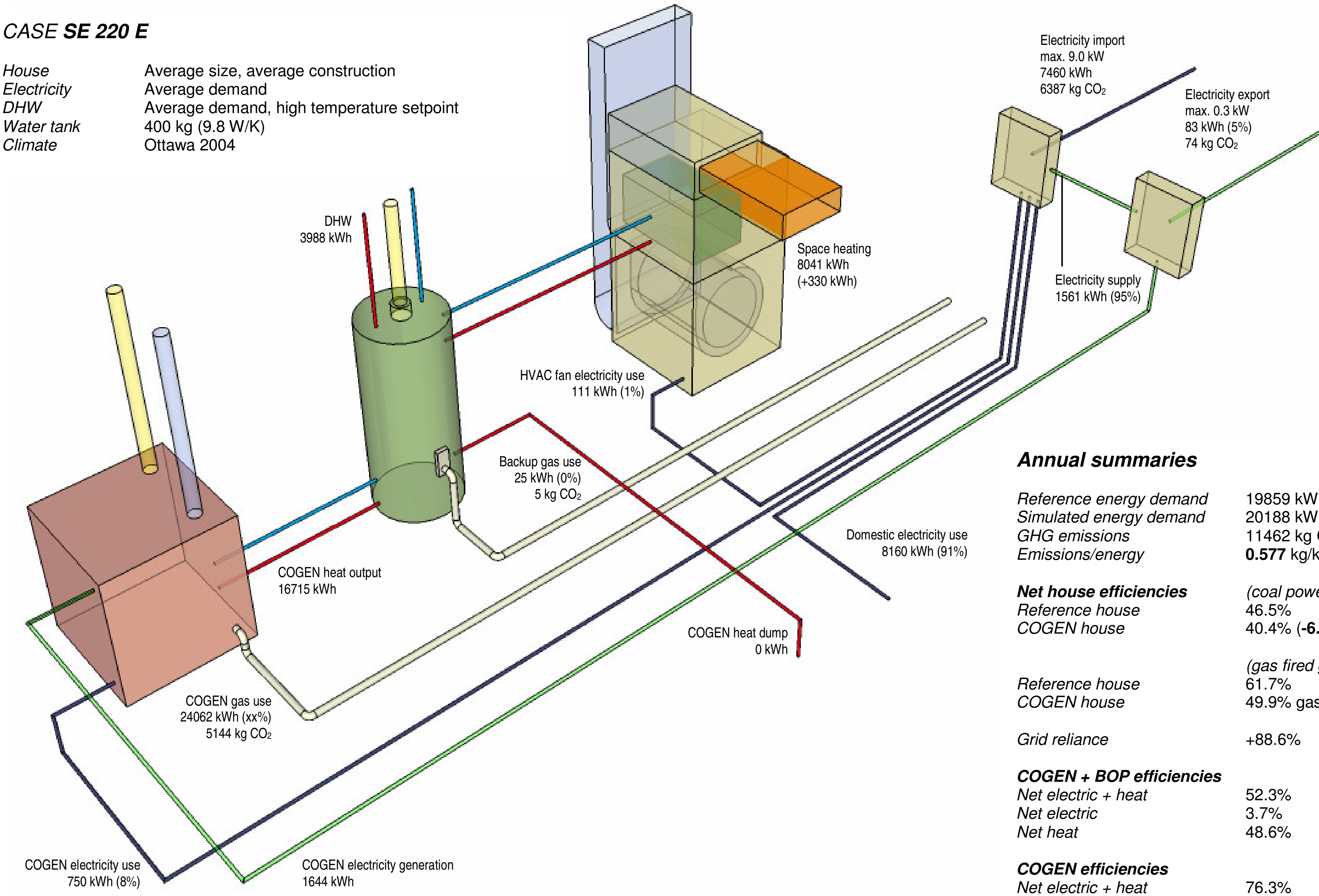
Reference energy demand	19859 kWh
Simulated energy demand	20181 kWh (**+1.6%**)
GHG emissions	10842 kg CO_2 (**+6.7%**)
Emissions/energy	**0.546** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	43.1% (**-3.4%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	54.7% gas (**-7.0%-p.**)
Grid reliance	+92.5%
COGEN + BOP efficiencies	
Net electric + heat	61.7%
Net electric	2.9%
Net heat	58.8%
COGEN efficiencies	
Net electric + heat	73.2%
Net electric	5.8%
Gross heat	61.3%
Net heat	61.3%
COGEN heat dump/output	0.0%



CASE SE 210 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

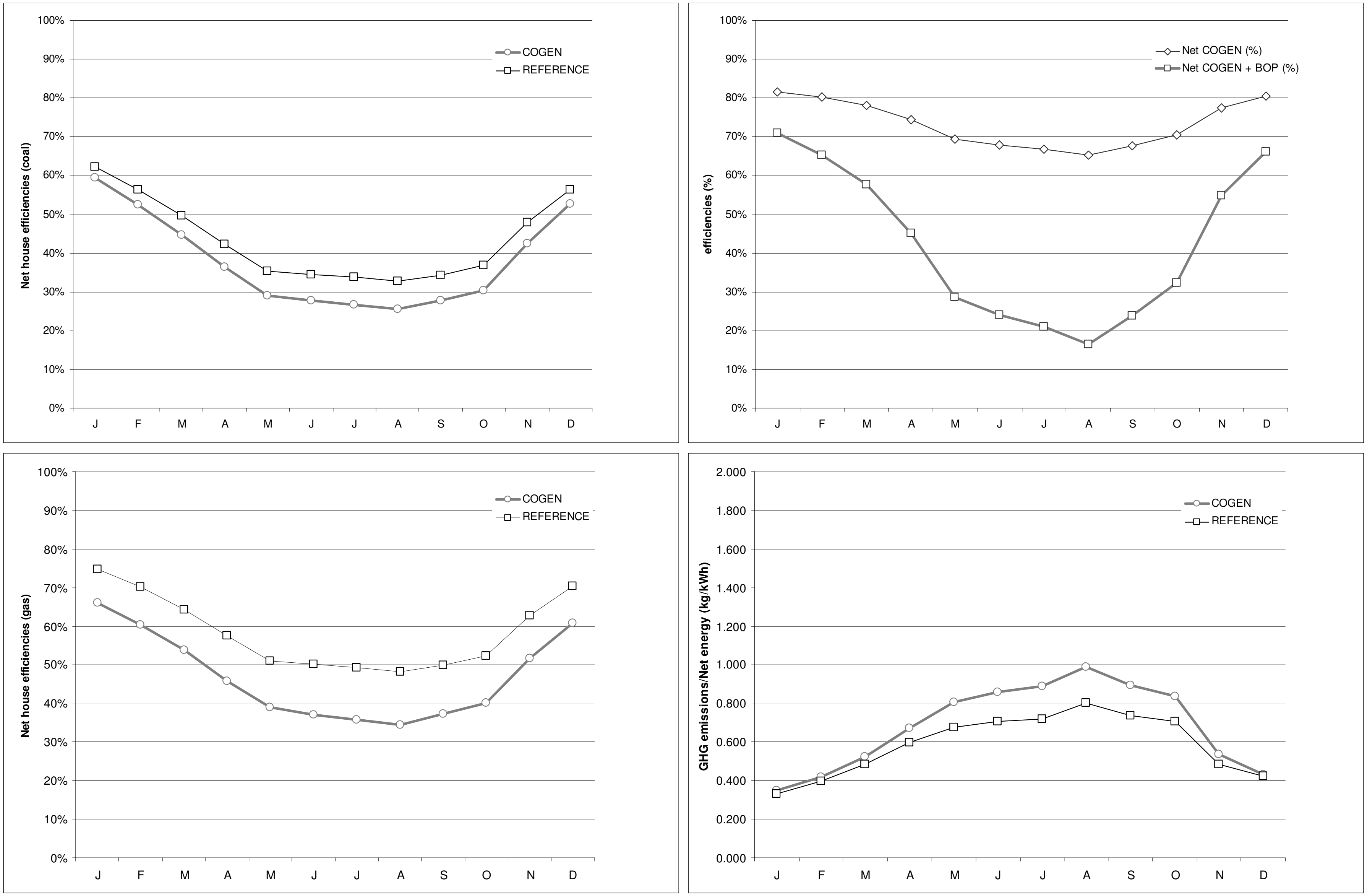
CASE ***SE 220 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	400 kg (9.8 W/K)
Climate	Ottawa 2004



Annual summaries

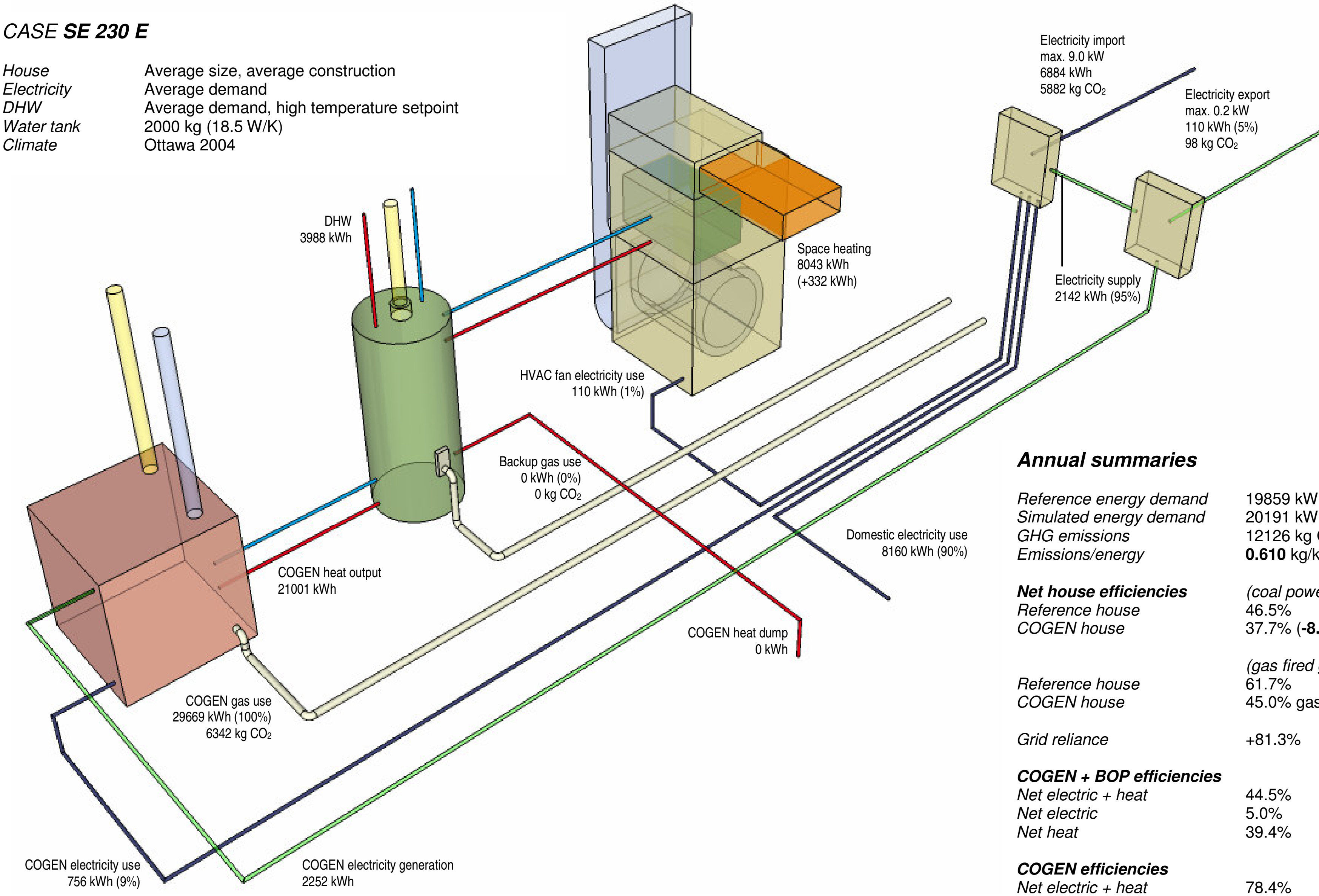
Reference energy demand	19859 kWh
Simulated energy demand	20188 kWh (**+1.7%**)
GHG emissions	11462 kg CO_2 (**+12.8%**)
Emissions/energy	**0.577** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	40.4% (**-6.1%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	49.9% gas (**-11.8%-p.**)
Grid reliance	+88.6%
COGEN + BOP efficiencies	
Net electric + heat	52.3%
Net electric	3.7%
Net heat	48.6%
COGEN efficiencies	
Net electric + heat	76.3%
Net electric	6.8%
Gross heat	69.5%
Net heat	69.5%
COGEN heat dump/output	0.0%



CASE SE 220 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

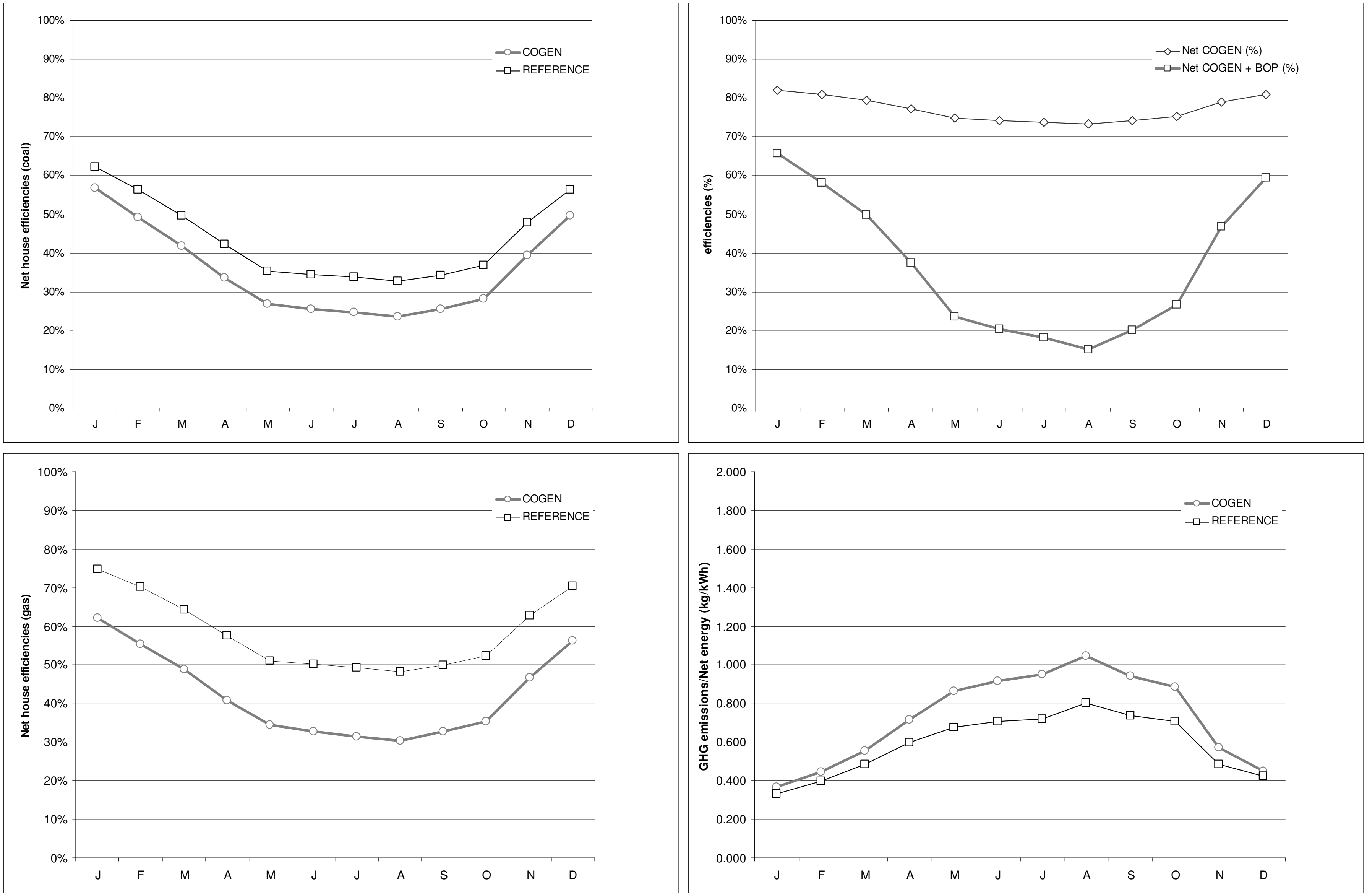
CASE ***SE 230 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	2000 kg (18.5 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20191 kWh (**+1.7%**)
GHG emissions	12126 kg CO_2 (**+19.4%**)
Emissions/energy	**0.610** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	37.7% (**-8.8%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	45.0% gas (**-16.7%-p.**)
Grid reliance	+81.3%
COGEN + BOP efficiencies	
Net electric + heat	44.5%
Net electric	5.0%
Net heat	39.4%
COGEN efficiencies	
Net electric + heat	78.4%
Net electric	7.6%
Gross heat	70.8%
Net heat	70.8%
COGEN heat dump/output	0.0%

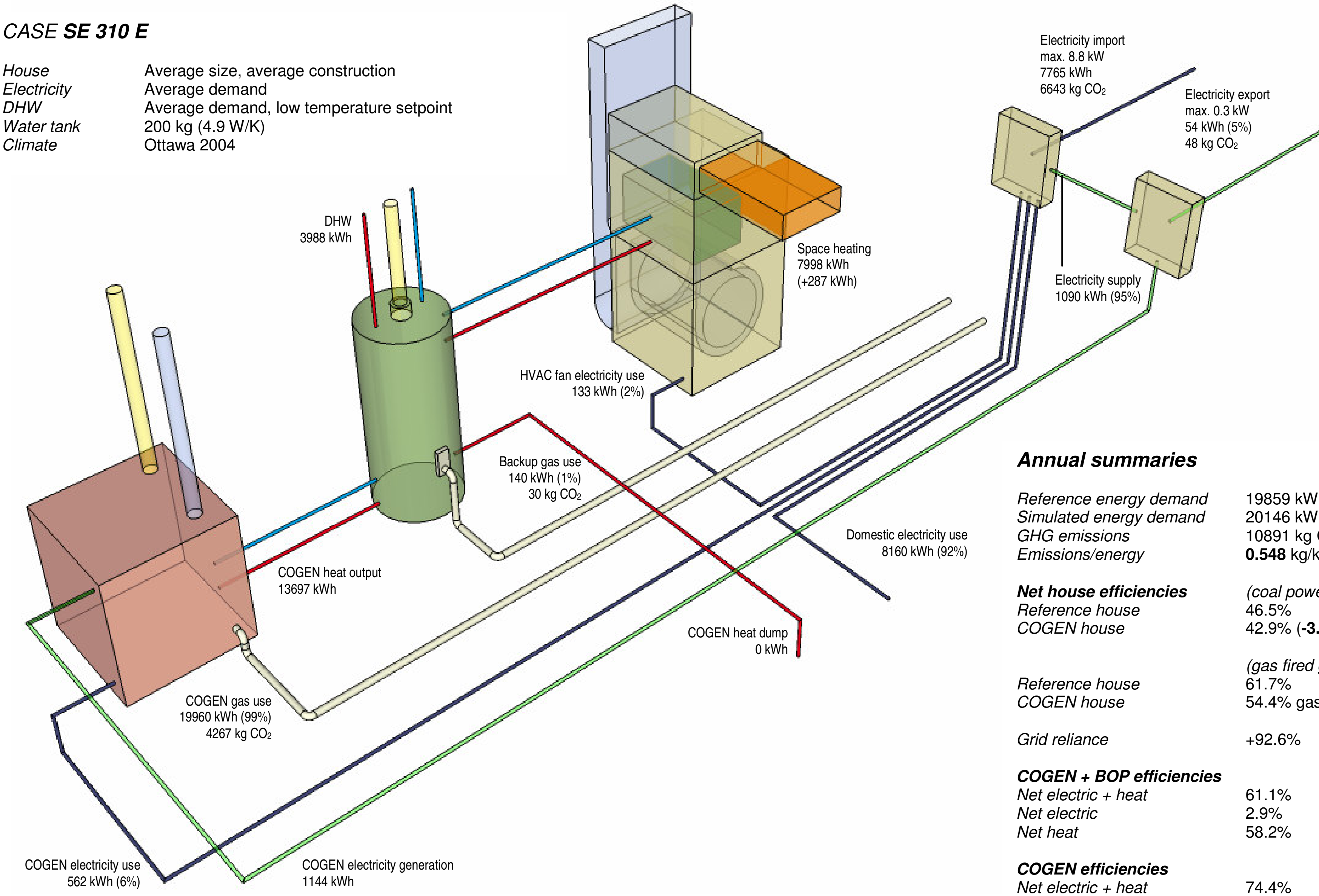


CASE SE 230 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

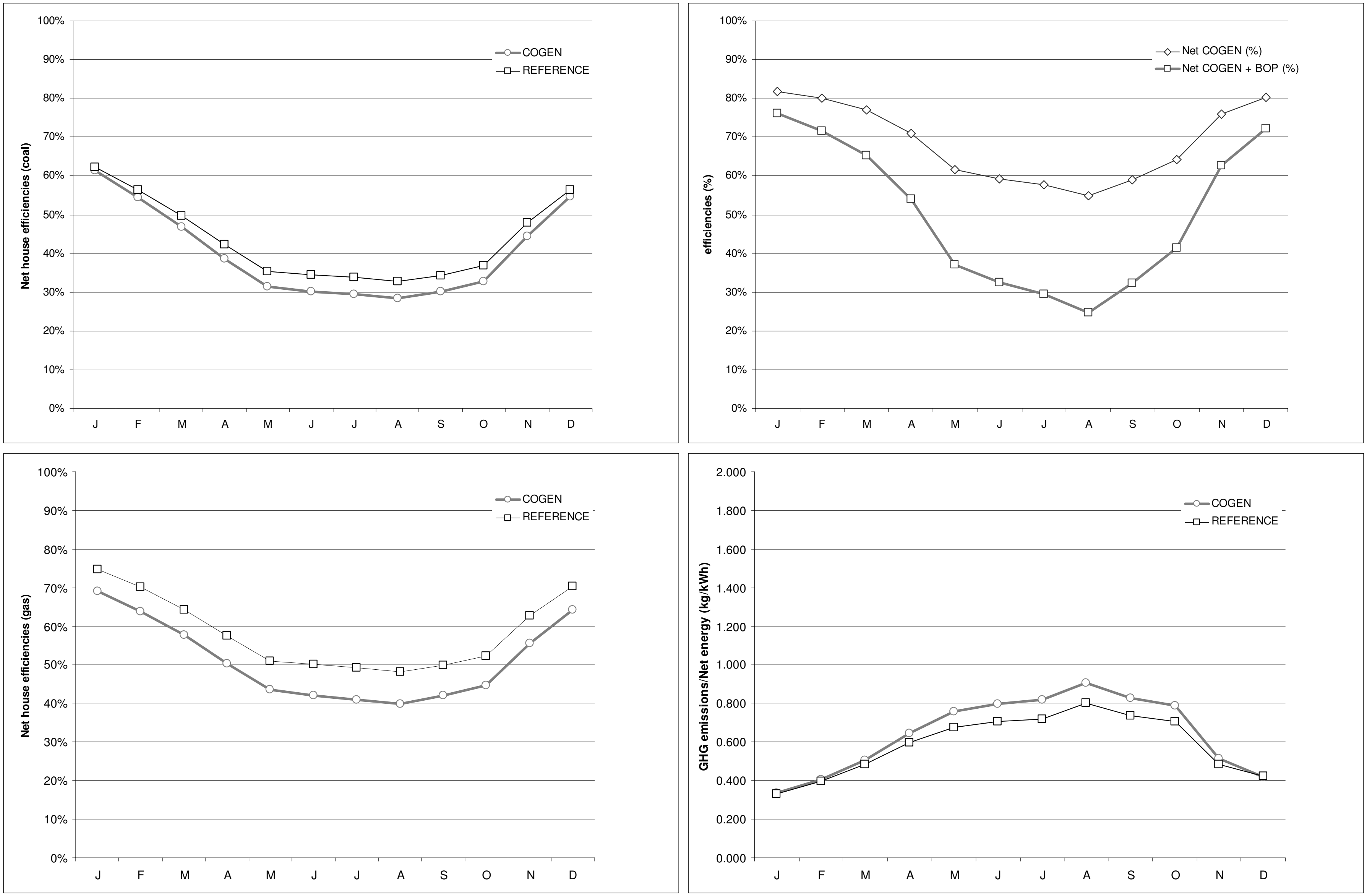
CASE ***SE 310 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, low temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

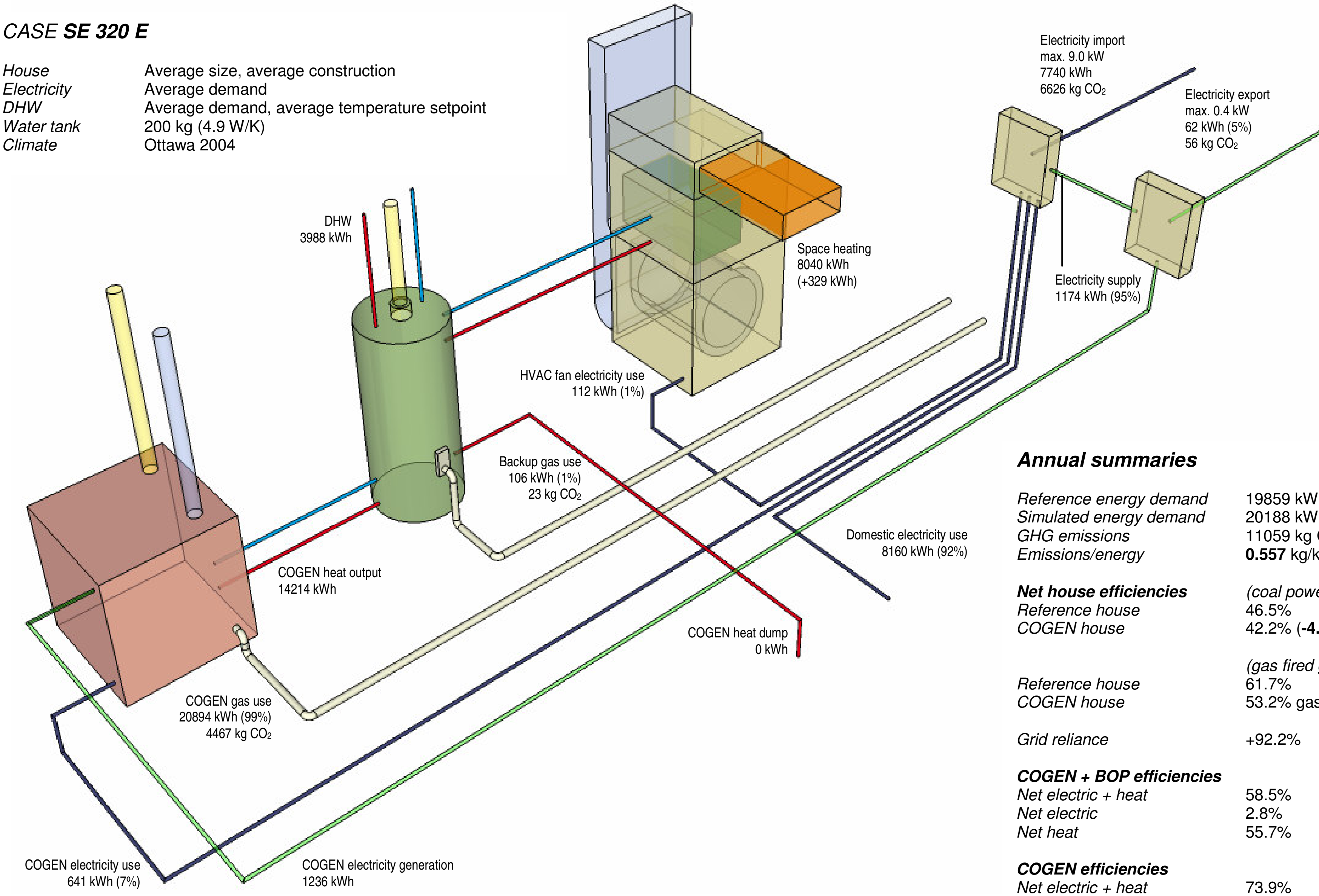
Reference energy demand	19859 kWh
Simulated energy demand	20146 kWh (**+1.4%**)
GHG emissions	10891 kg CO_2 (**+7.2%**)
Emissions/energy	**0.548** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	42.9% (**-3.6%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	54.4% gas (**-7.3%-p.**)
Grid reliance	+92.6%
COGEN + BOP efficiencies	
Net electric + heat	61.1%
Net electric	2.9%
Net heat	58.2%
COGEN efficiencies	
Net electric + heat	74.4%
Net electric	5.7%
Gross heat	68.6%
Net heat	68.6%
COGEN heat dump/output	0.0%



CASE SE 310 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

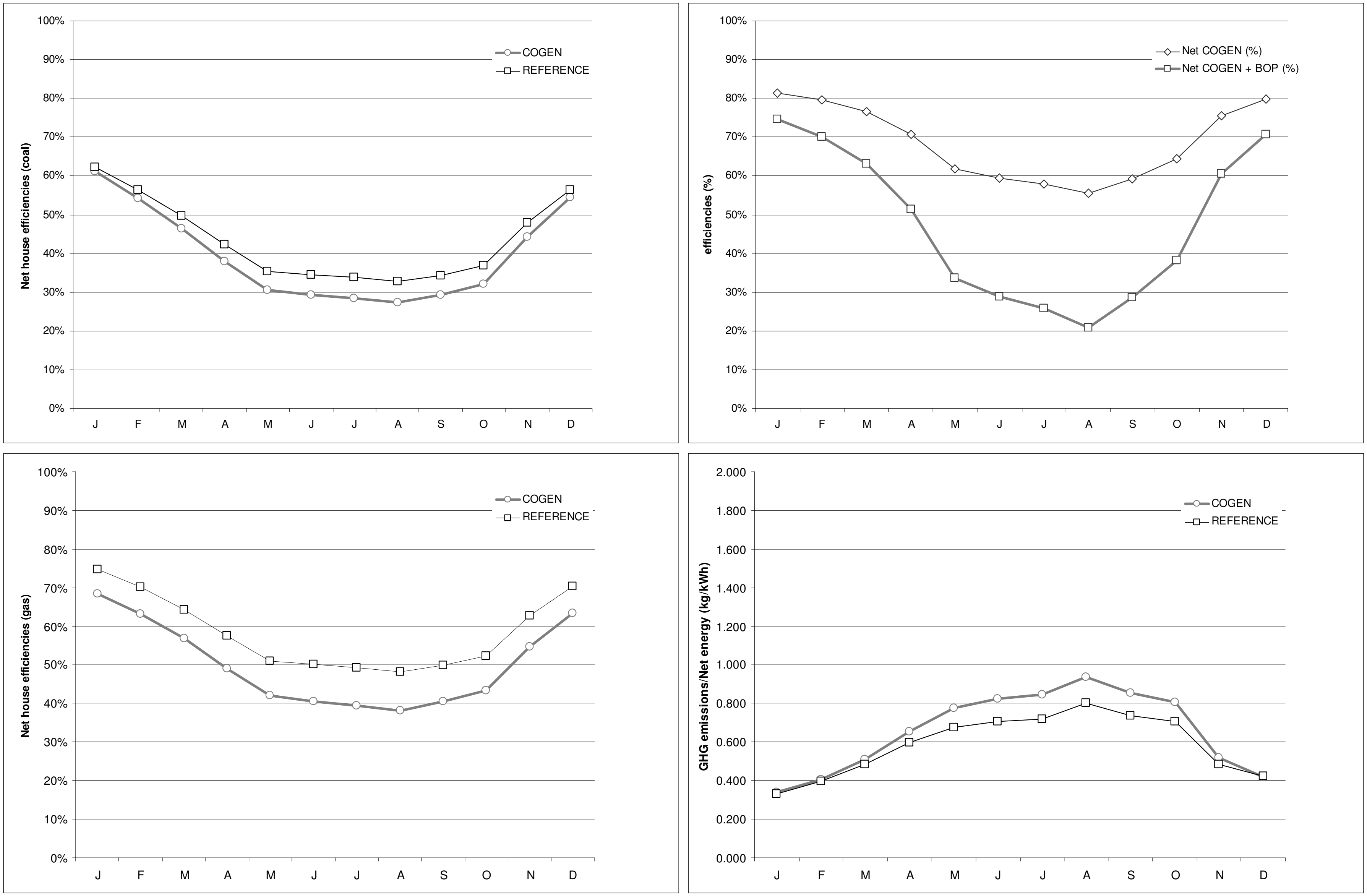
CASE ***SE 320 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, average temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

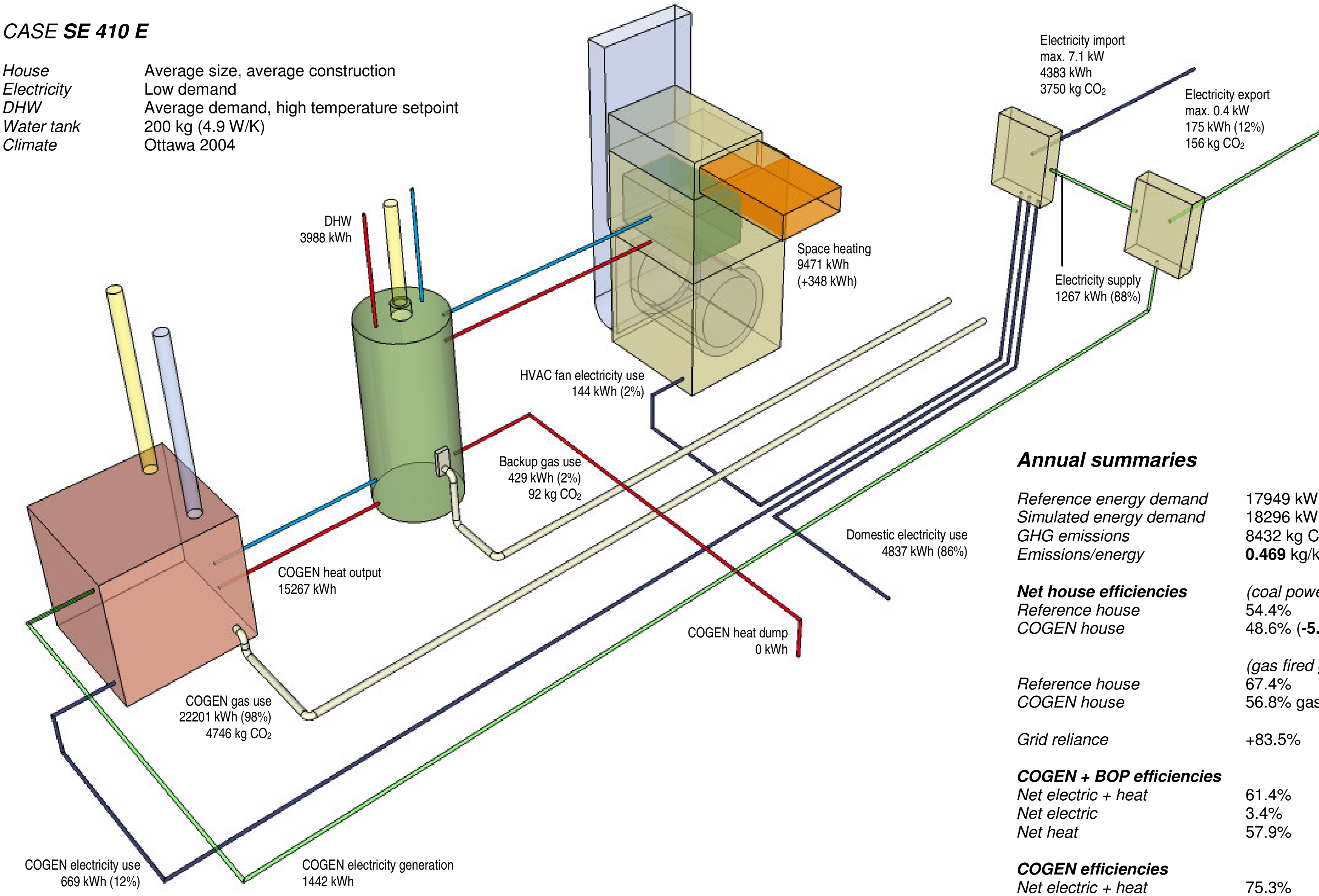
Reference energy demand	19859 kWh
Simulated energy demand	20188 kWh (**+1.7%**)
GHG emissions	11059 kg CO_2 (**+8.9%**)
Emissions/energy	**0.557** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	42.2% (**-4.3%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	53.2% gas (**-8.5%-p.**)
Grid reliance	+92.2%
COGEN + BOP efficiencies	
Net electric + heat	58.5%
Net electric	2.8%
Net heat	55.7%
COGEN efficiencies	
Net electric + heat	73.9%
Net electric	5.9%
Gross heat	68.0%
Net heat	68.0%
COGEN heat dump/output	0.0%



CASE SE 320 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

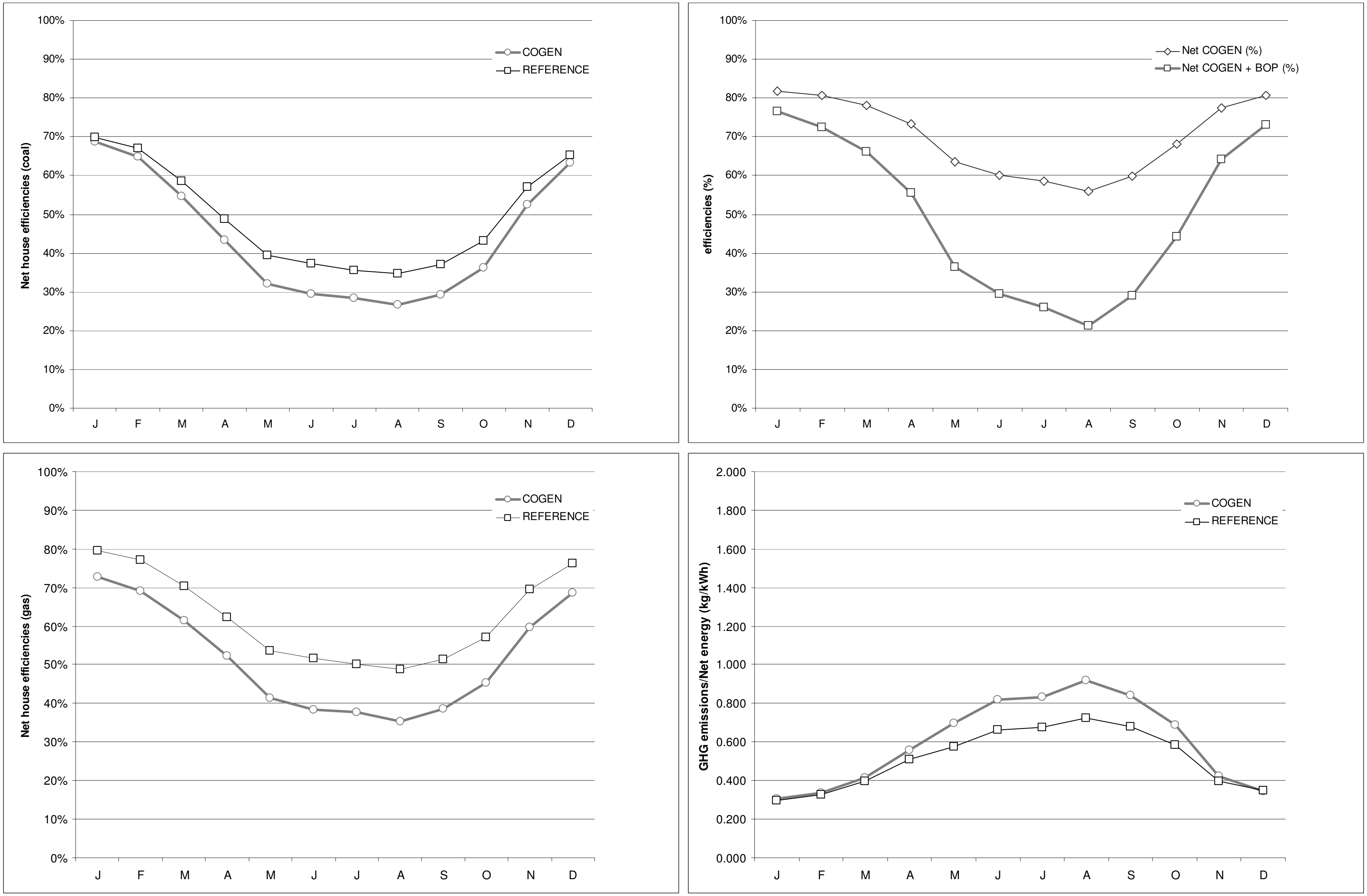
CASE ***SE 410 E***

House	Average size, average construction
Electricity	Low demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	17949 kWh
Simulated energy demand	18296 kWh (**+1.9%**)
GHG emissions	8432 kg CO_2 (**+10.2%**)
Emissions/energy	**0.469** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	54.4%
COGEN house	48.6% (**-5.8%-p.**)
	(gas fired grid)
Reference house	67.4%
COGEN house	56.8% gas (**-10.6%-p.**)
Grid reliance	+83.5%
COGEN + BOP efficiencies	
Net electric + heat	61.4%
Net electric	3.4%
Net heat	57.9%
COGEN efficiencies	
Net electric + heat	75.3%
Net electric	6.5%
Gross heat	68.8%
Net heat	68.8%
COGEN heat dump/output	0.0%

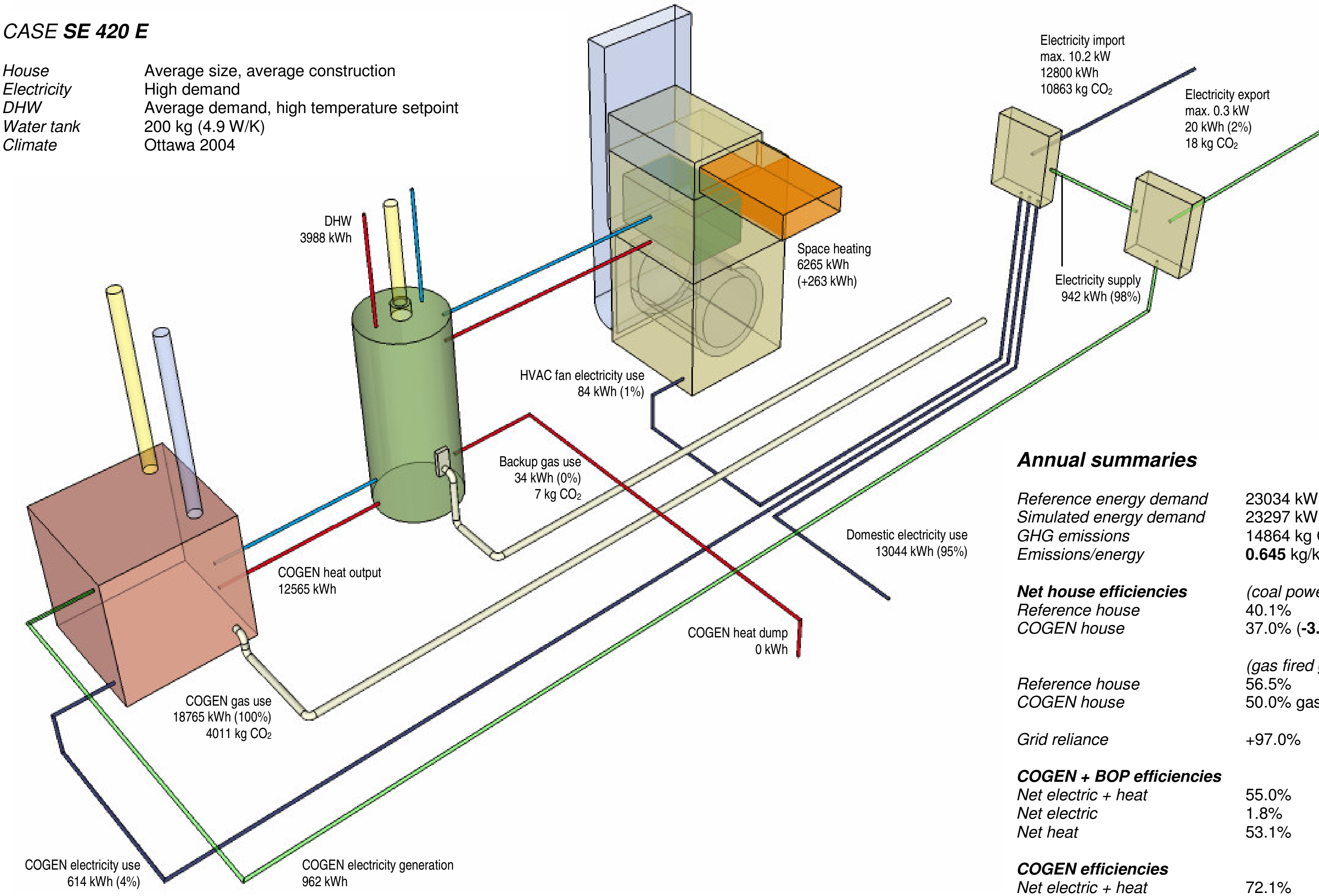


CASE SE 410 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

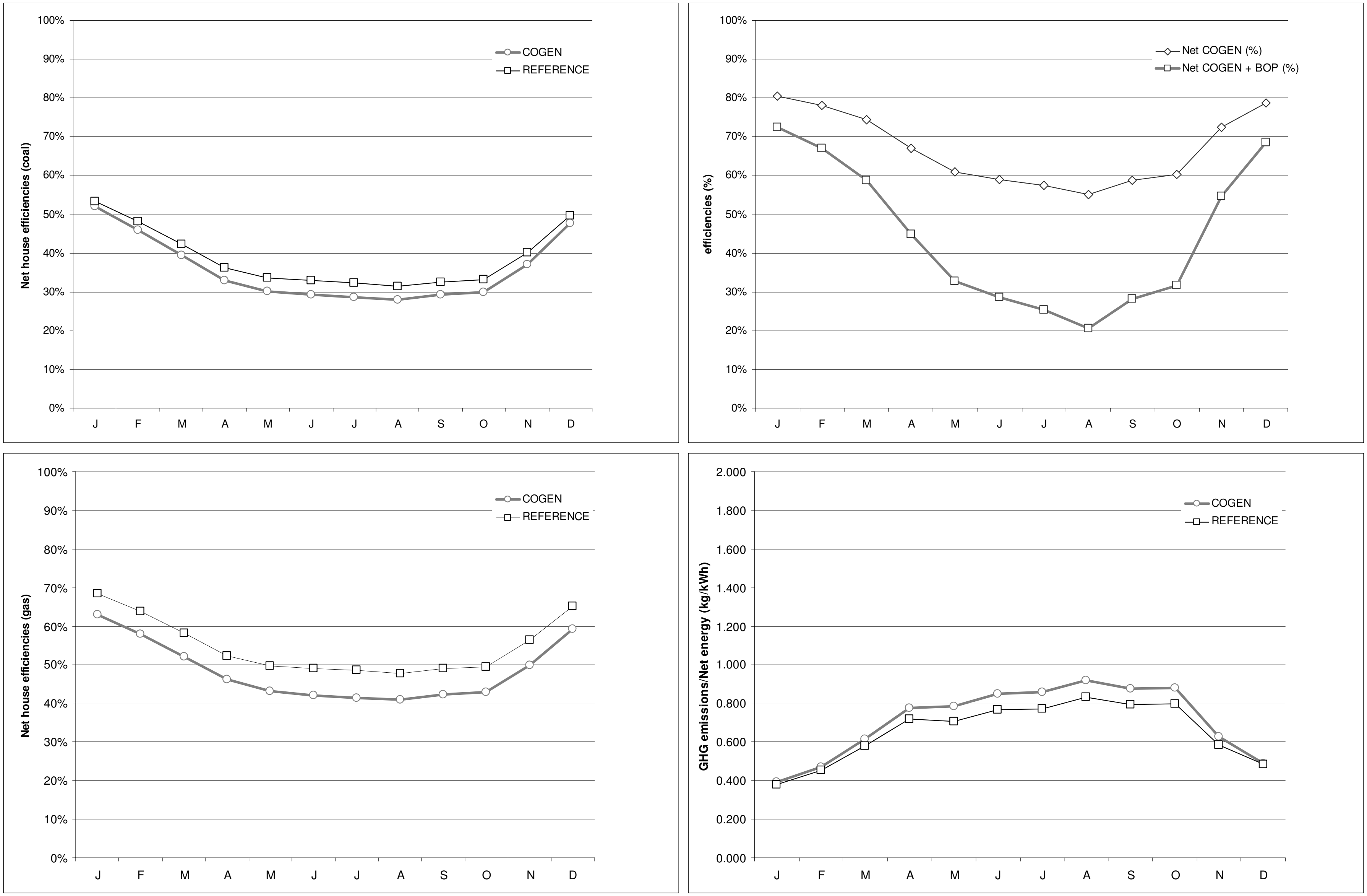
CASE ***SE 420 E***

House	Average size, average construction
Electricity	High demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

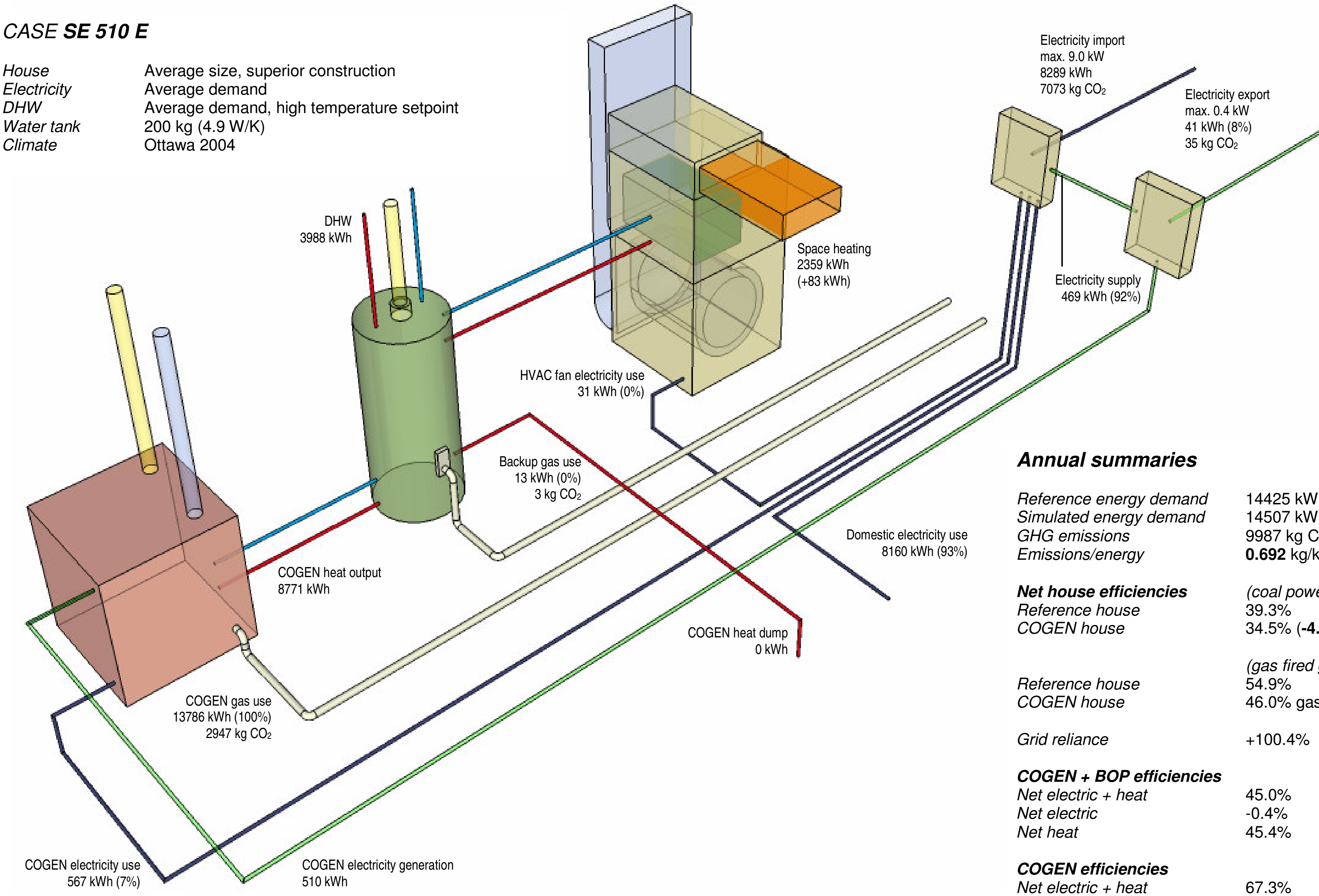
Reference energy demand	23034 kWh
Simulated energy demand	23297 kWh (**+1.1%**)
GHG emissions	14864 kg CO_2 (**+7.4%**)
Emissions/energy	**0.645** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	40.1%
COGEN house	37.0% (**-3.1%-p.**)
	(gas fired grid)
Reference house	56.5%
COGEN house	50.0% gas (**-6.5%-p.**)
Grid reliance	+97.0%
COGEN + BOP efficiencies	
Net electric + heat	55.0%
Net electric	1.8%
Net heat	53.1%
COGEN efficiencies	
Net electric + heat	72.1%
Net electric	5.1%
Gross heat	67.0%
Net heat	67.0%
COGEN heat dump/output	0.0%



CASE SE 420 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

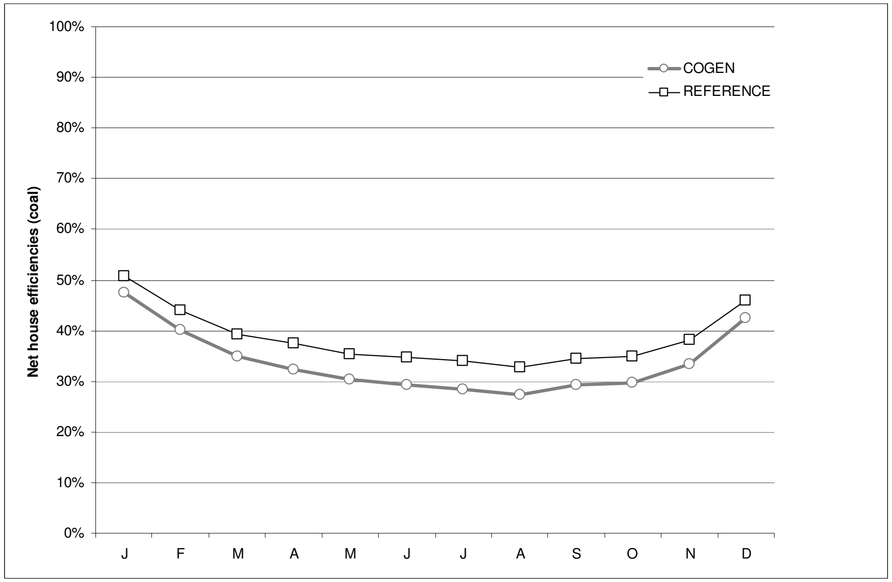
CASE ***SE 510 E***

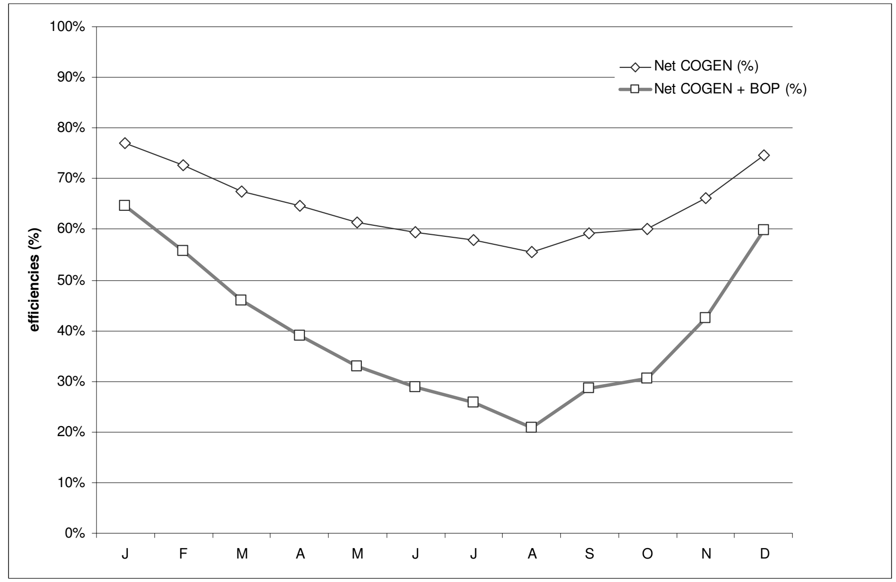
House	Average size, superior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004

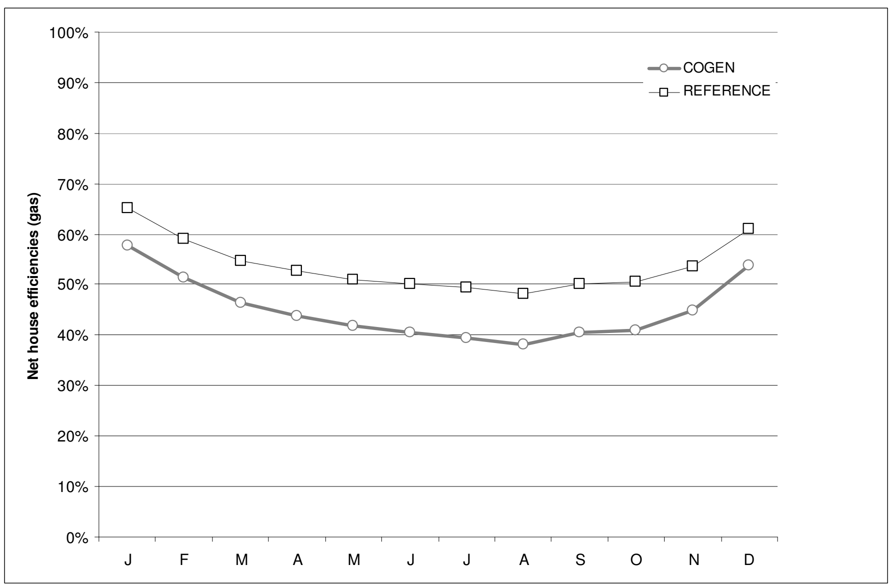


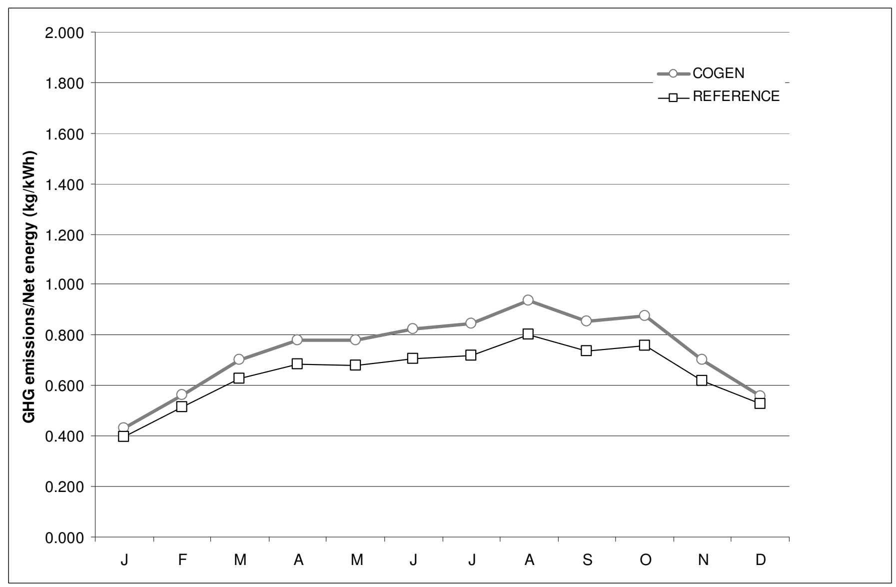
Annual summaries

Reference energy demand	14425 kWh
Simulated energy demand	14507 kWh (**+0.6%**)
GHG emissions	9987 kg CO_2 (**+12.8%**)
Emissions/energy	**0.692** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	39.3%
COGEN house	34.5% (**-4.8%-p.**)
	(gas fired grid)
Reference house	54.9%
COGEN house	46.0% gas (**-8.9%-p.**)
Grid reliance	+100.4%
COGEN + BOP efficiencies	
Net electric + heat	45.0%
Net electric	-0.4%
Net heat	45.4%
COGEN efficiencies	
Net electric + heat	67.3%
Net electric	3.7%
Gross heat	63.6%
Net heat	63.6%
COGEN heat dump/output	0.0%







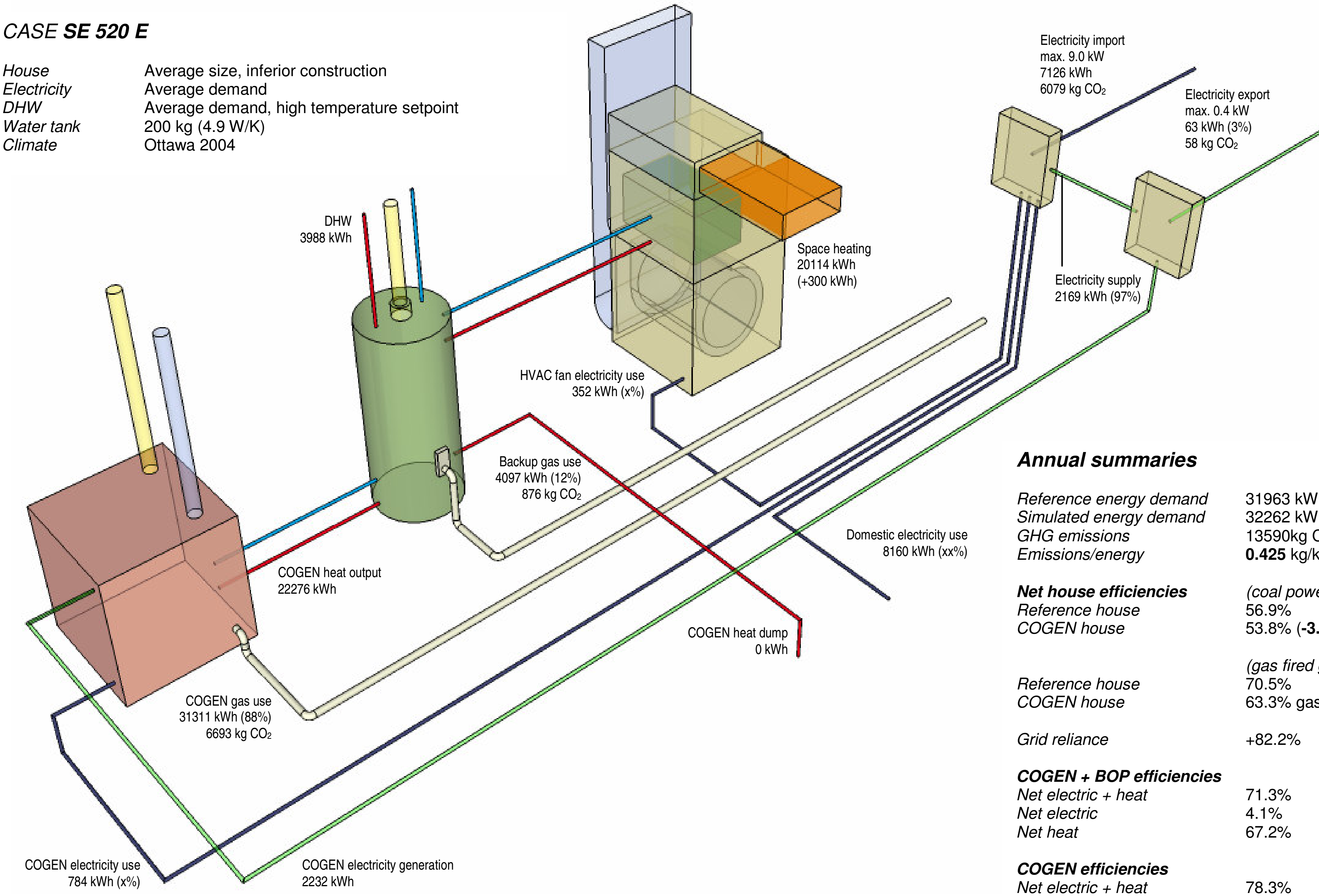


CASE SE 510 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

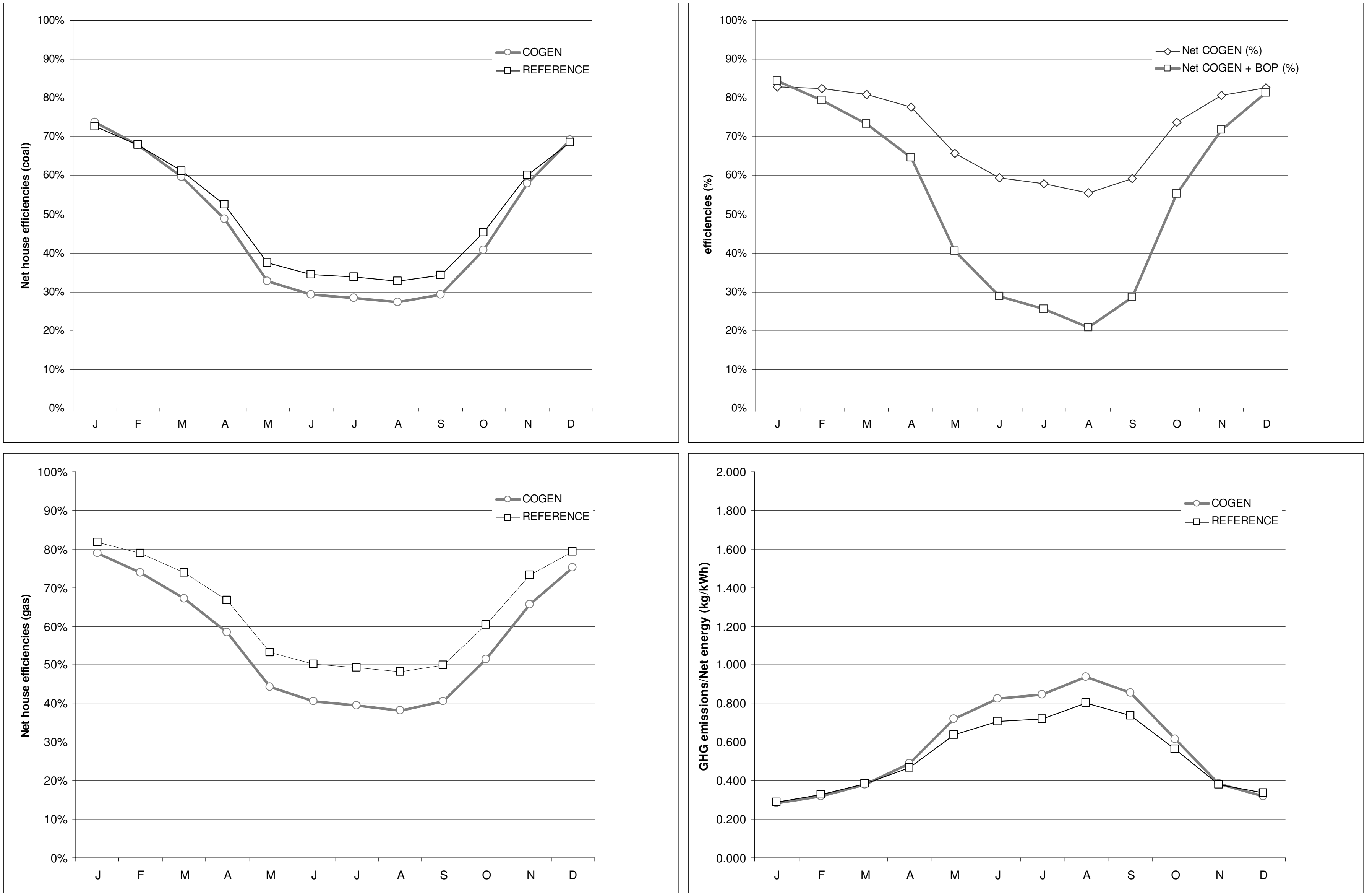
CASE **SE 520 E**

House	Average size, inferior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	31963 kWh
Simulated energy demand	32262 kWh (**+0.9%**)
GHG emissions	13590kg CO_2 (**+4.1%**)
Emissions/energy	**0.425** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	56.9%
COGEN house	53.8% (**-3.1%-p.**)
	(gas fired grid)
Reference house	70.5%
COGEN house	63.3% gas (**-7.2%-p.**)
Grid reliance	+82.2%
COGEN + BOP efficiencies	
Net electric + heat	71.3%
Net electric	4.1%
Net heat	67.2%
COGEN efficiencies	
Net electric + heat	78.3%
Net electric	7.1%
Gross heat	71.1%
Net heat	71.1%
COGEN heat dump/output	0.0%

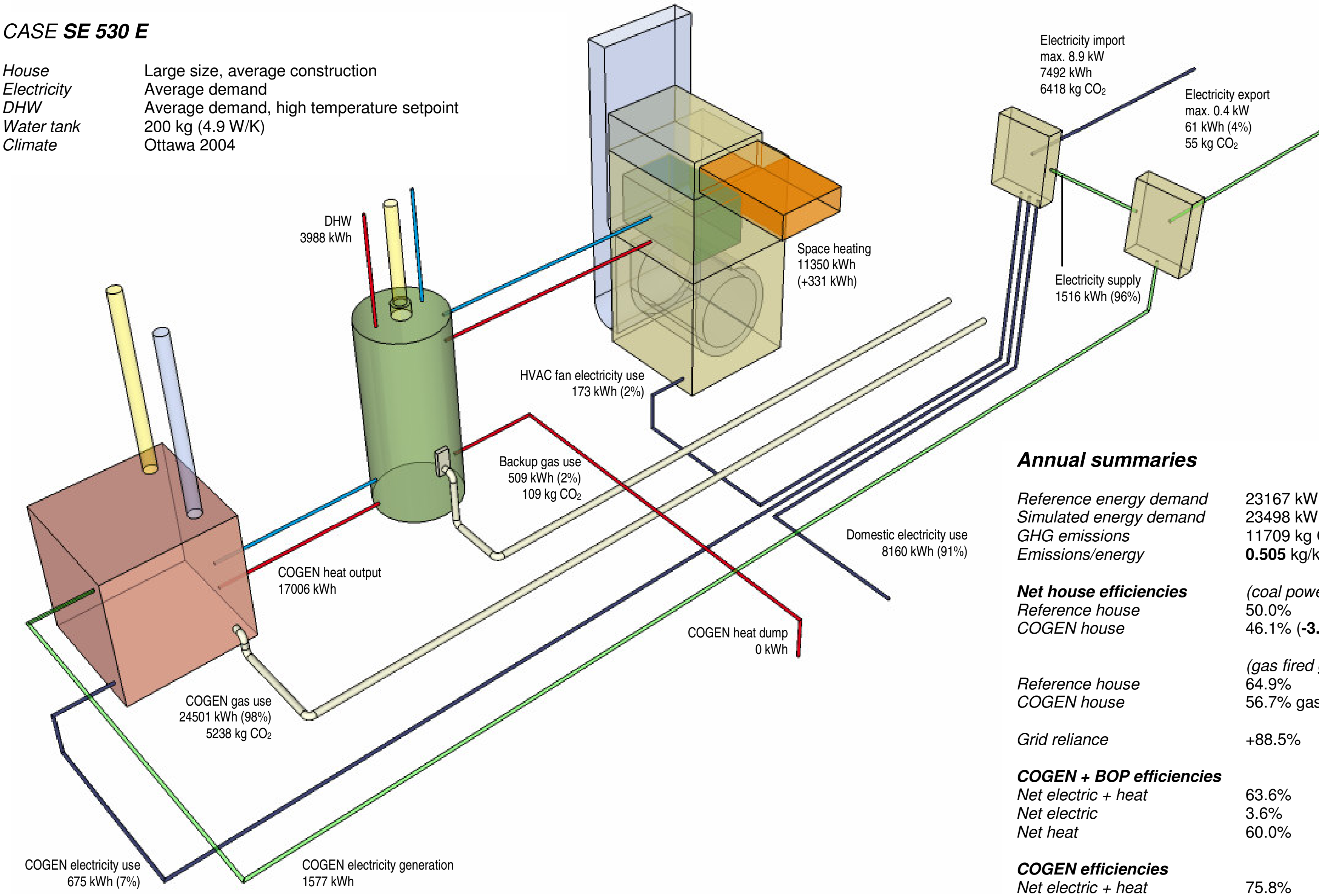


CASE SE 520 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

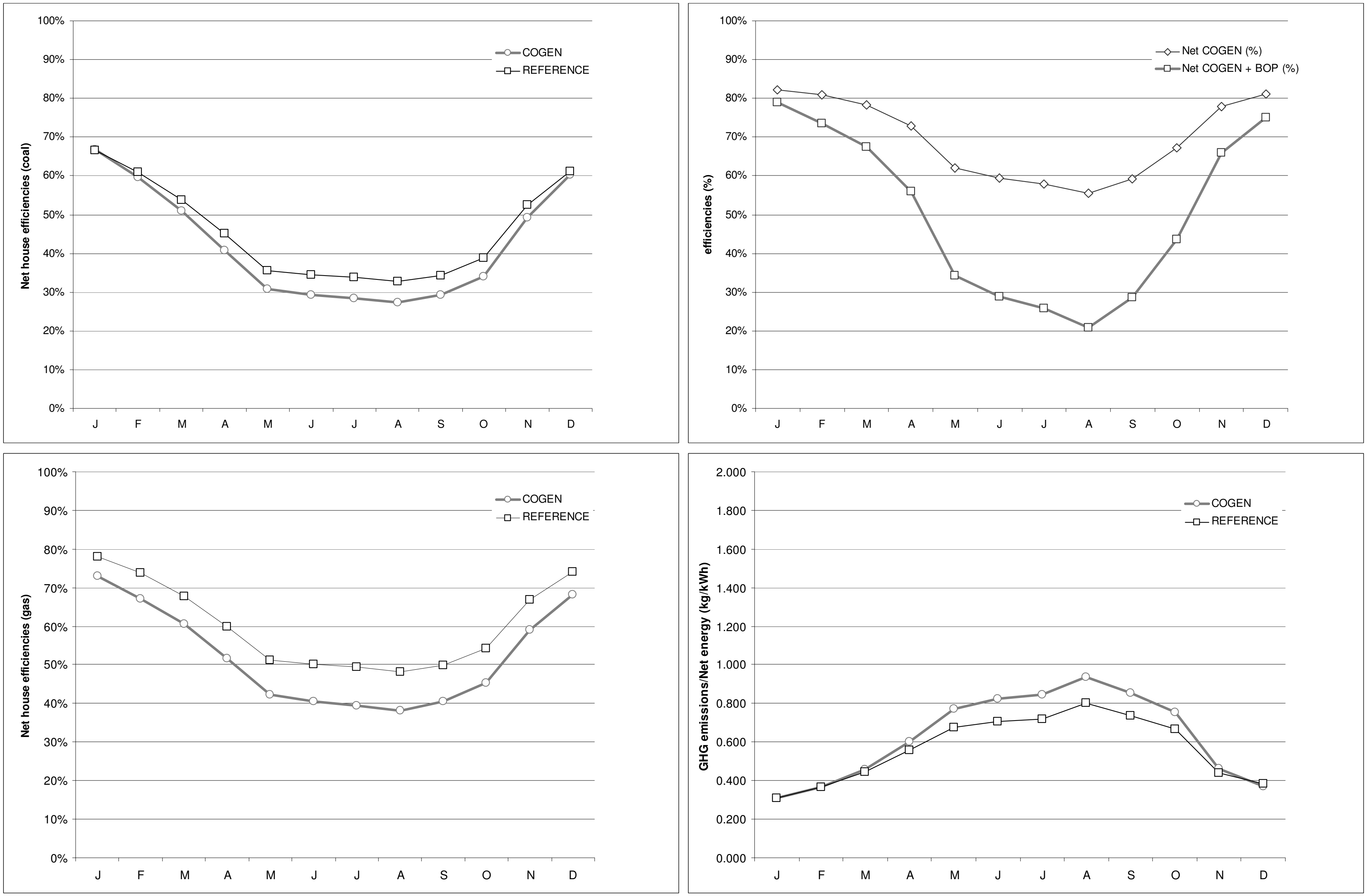
CASE ***SE 530 E***

House	Large size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	23167 kWh
Simulated energy demand	23498 kWh (**+1.4%**)
GHG emissions	11709 kg CO_2 (**+7.1%**)
Emissions/energy	**0.505** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	50.0%
COGEN house	46.1% (**-3.9%-p.**)
	(gas fired grid)
Reference house	64.9%
COGEN house	56.7% gas (**-8.2%-p.**)
Grid reliance	+88.5%
COGEN + BOP efficiencies	
Net electric + heat	63.6%
Net electric	3.6%
Net heat	60.0%
COGEN efficiencies	
Net electric + heat	75.8%
Net electric	6.4%
Gross heat	69.4%
Net heat	69.4%
COGEN heat dump/output	0.0%

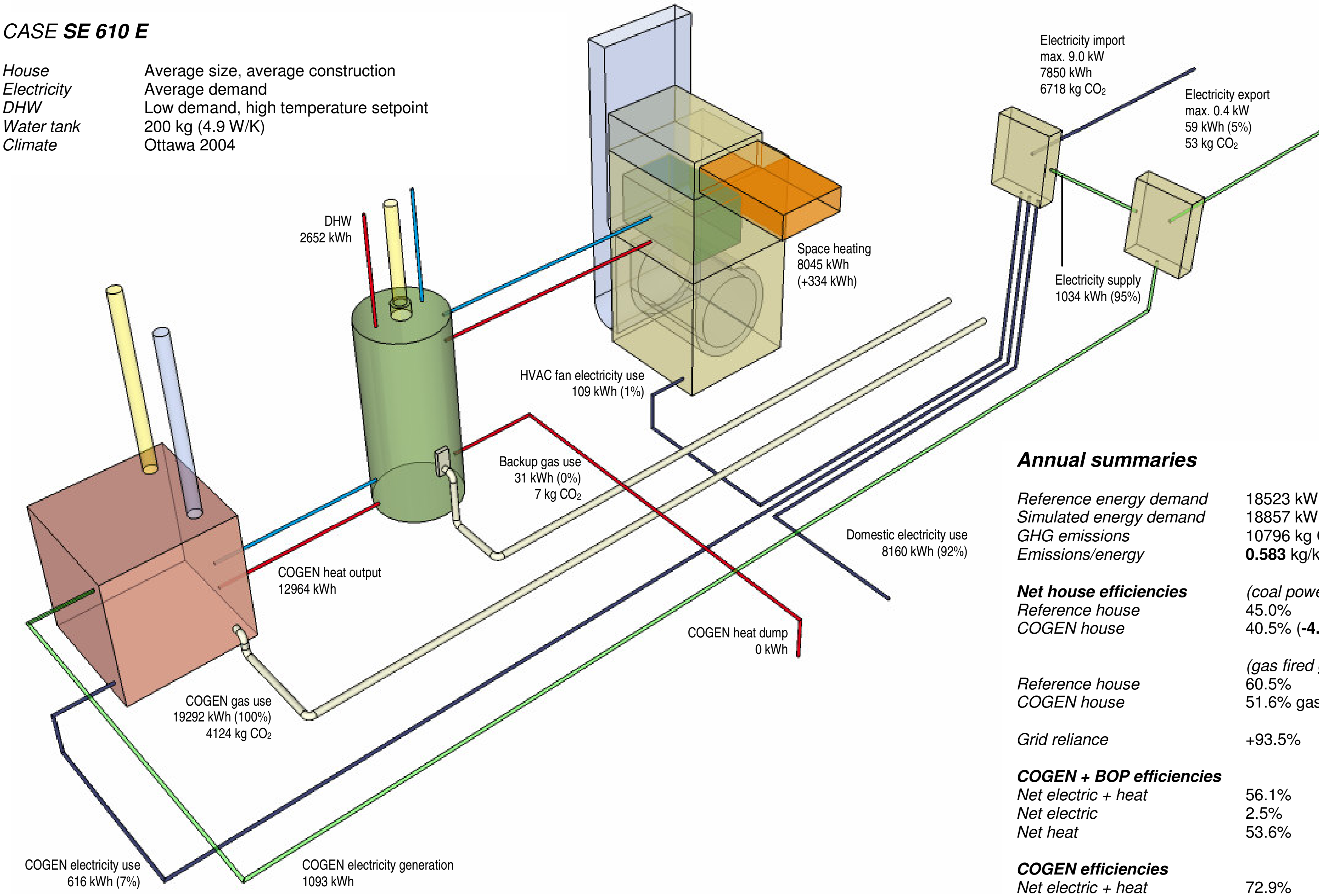


CASE SE 530 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

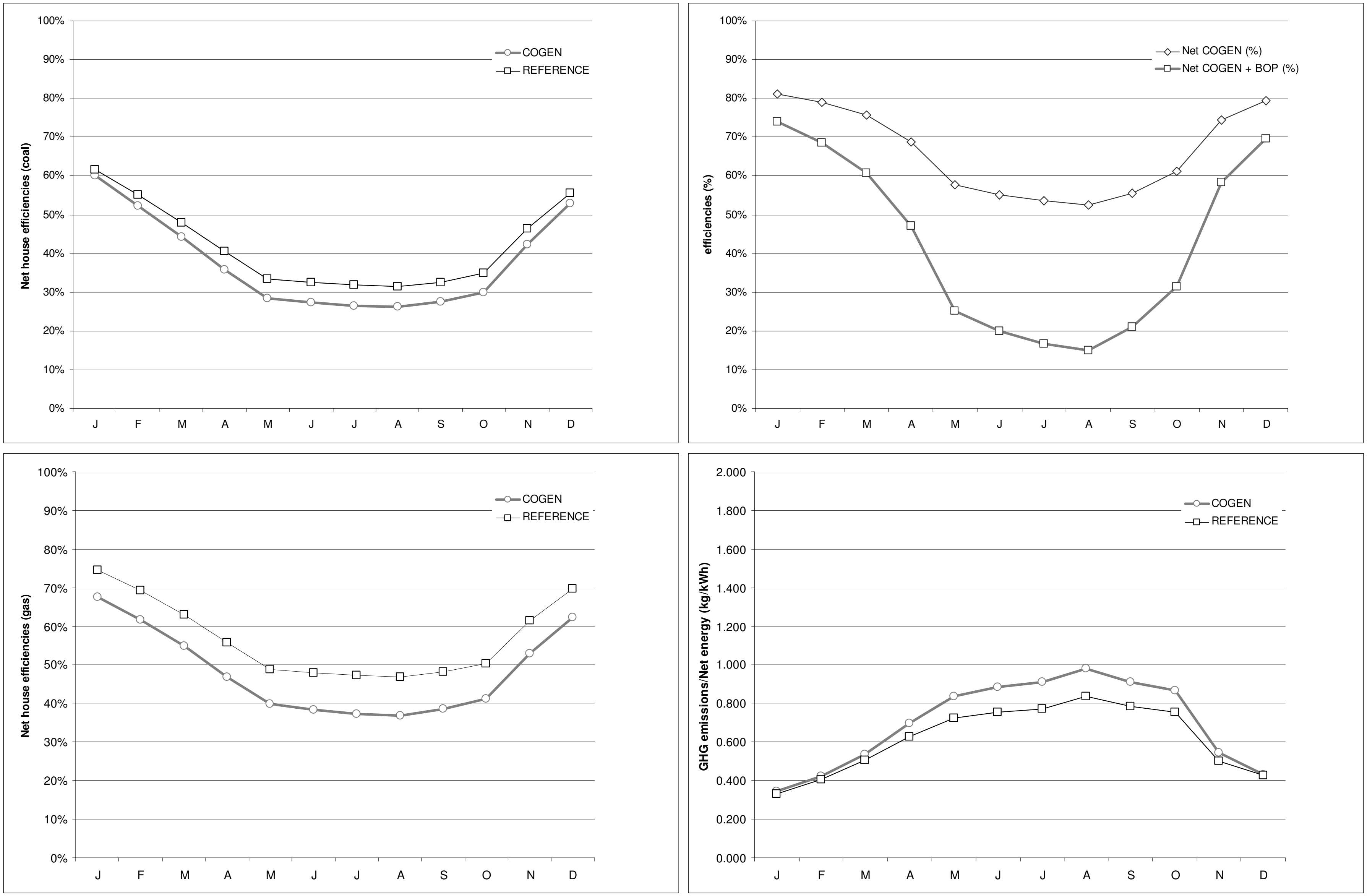
CASE ***SE 610 E***

House	Average size, average construction
Electricity	Average demand
DHW	Low demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

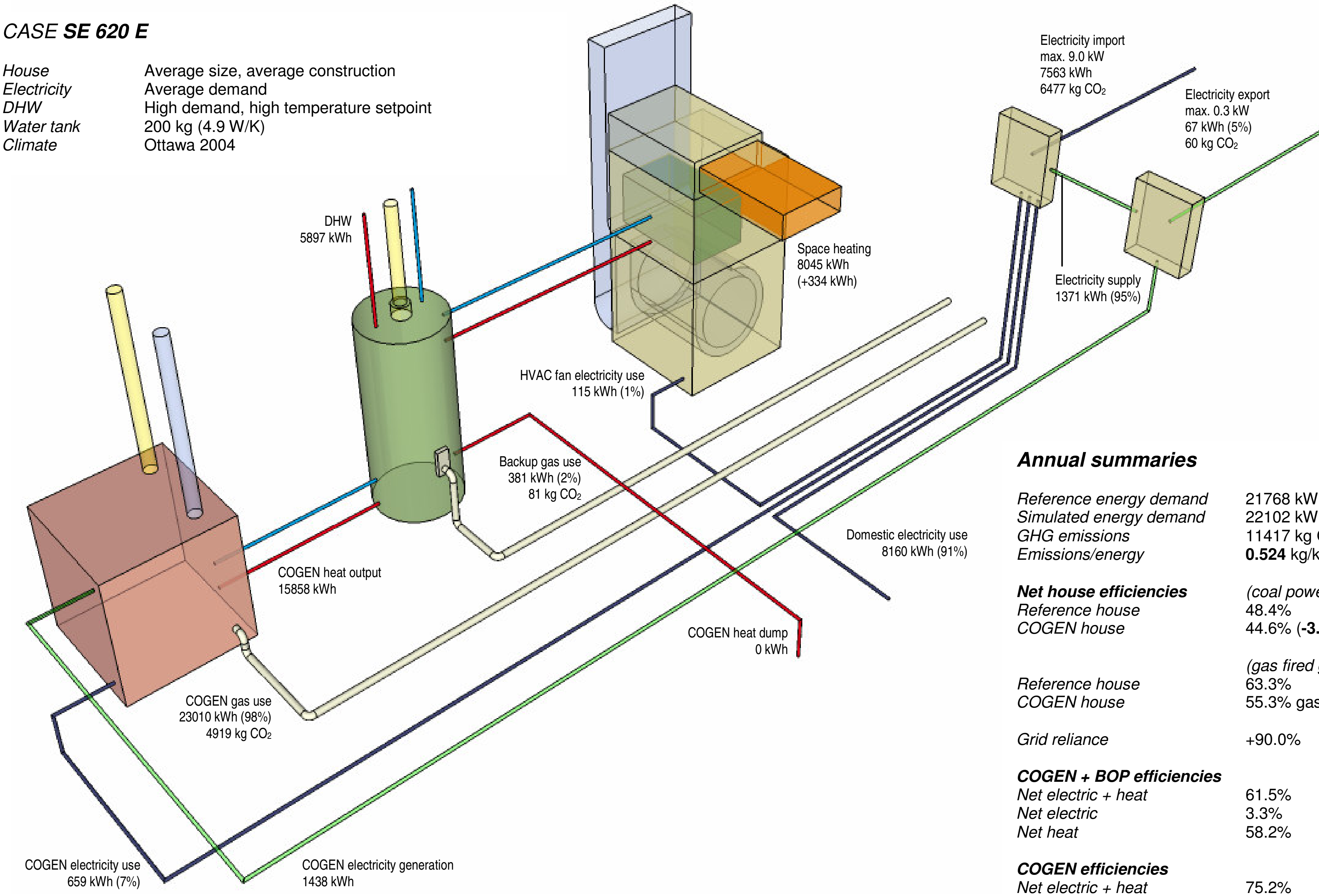
Reference energy demand	18523 kWh
Simulated energy demand	18857 kWh (**+1.8%**)
GHG emissions	10796 kg CO_2 (**+9.9%**)
Emissions/energy	**0.583** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	45.0%
COGEN house	40.5% (**-4.5%-p.**)
	(gas fired grid)
Reference house	60.5%
COGEN house	51.6% gas (**-8.9%-p.**)
Grid reliance	+93.5%
COGEN + BOP efficiencies	
Net electric + heat	56.1%
Net electric	2.5%
Net heat	53.6%
COGEN efficiencies	
Net electric + heat	72.9%
Net electric	5.7%
Gross heat	67.2%
Net heat	67.2%
COGEN heat dump/output	0.0%



CASE SE 610 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

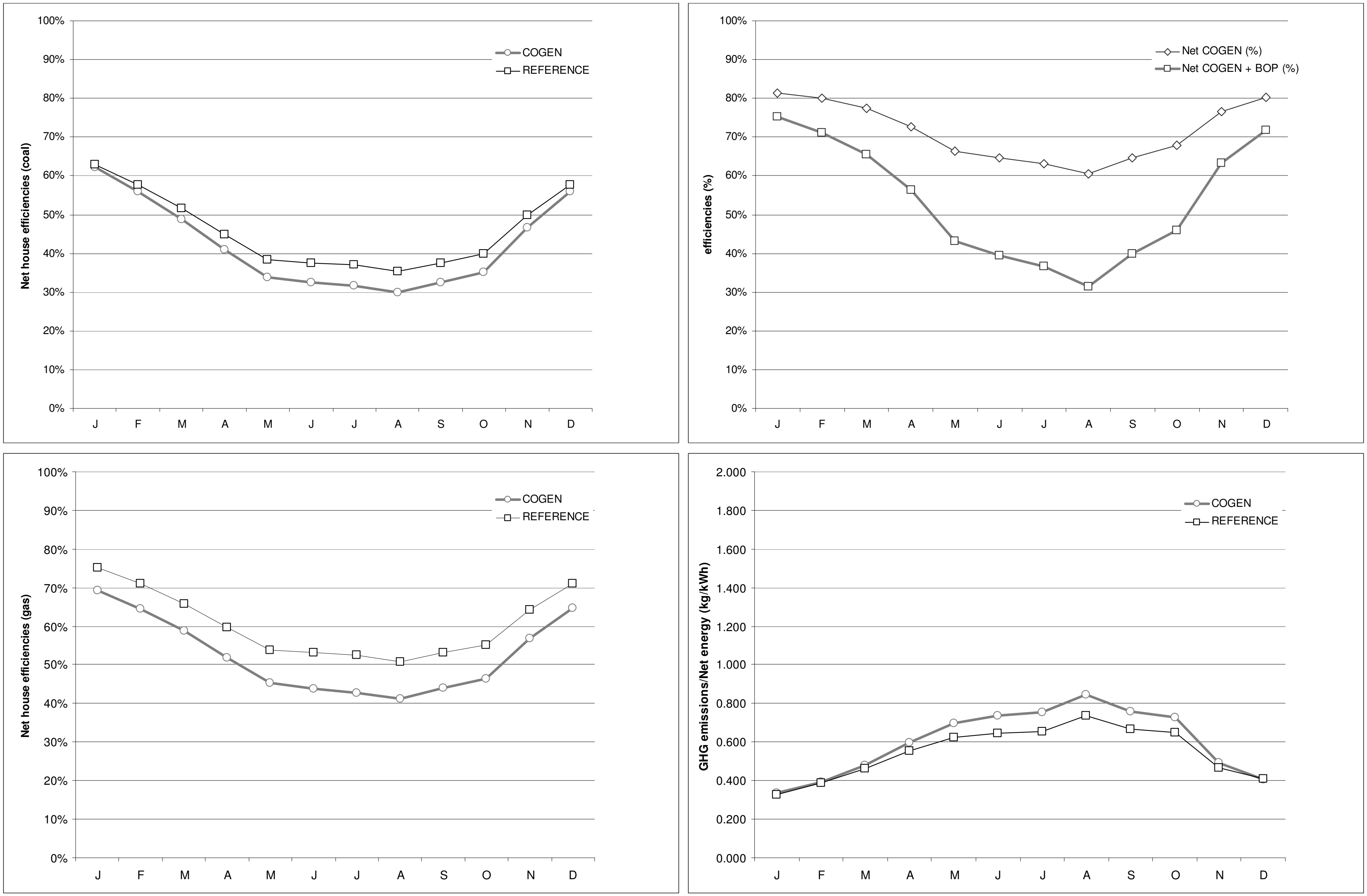
CASE ***SE 620 E***

House	Average size, average construction
Electricity	Average demand
DHW	High demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

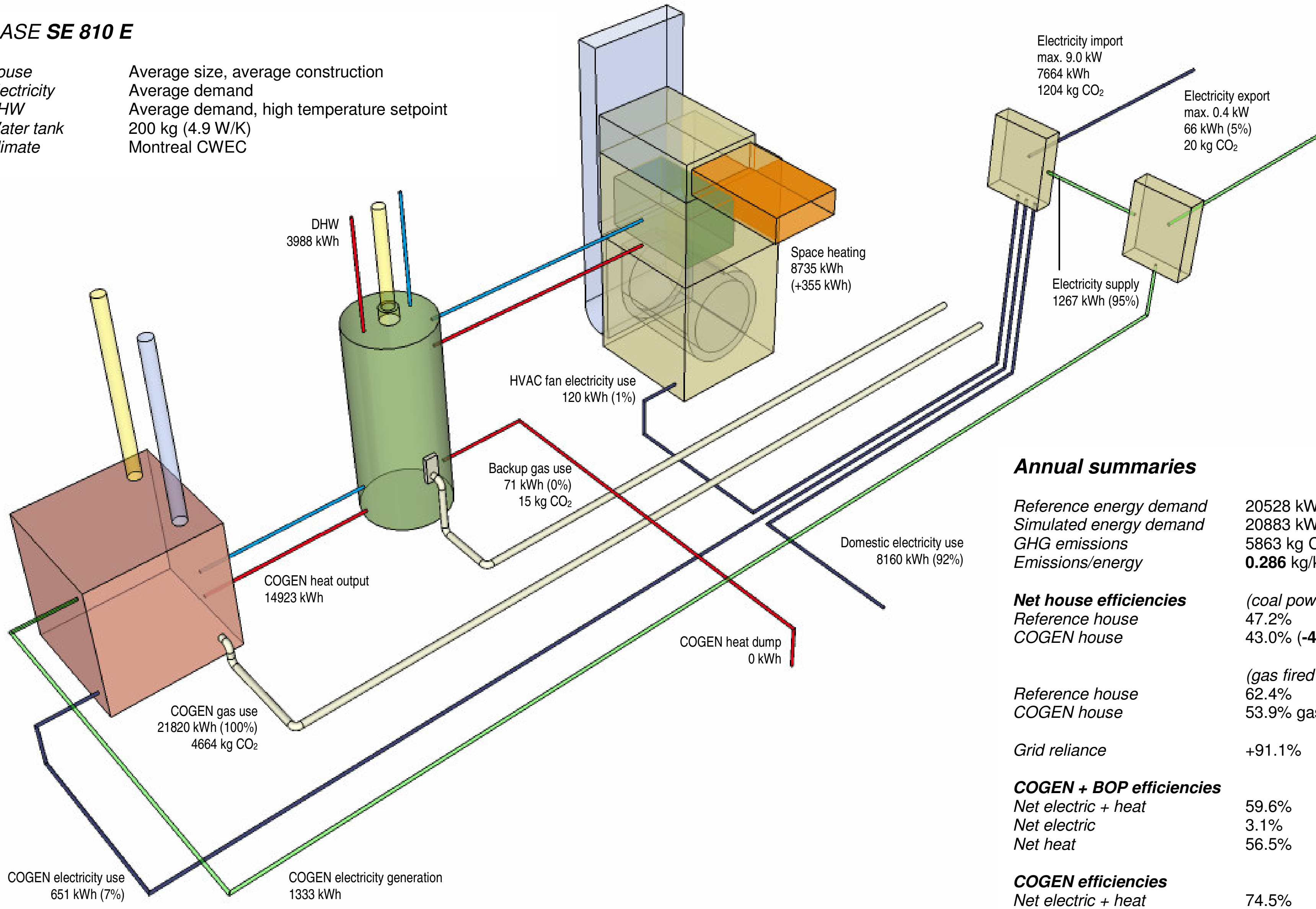
Reference energy demand	21768 kWh
Simulated energy demand	22102 kWh (**+1.5%**)
GHG emissions	11417 kg CO_2 (**+7.4%**)
Emissions/energy	**0.524** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	48.4%
COGEN house	44.6% (**-3.9%-p.**)
	(gas fired grid)
Reference house	63.3%
COGEN house	55.3% gas (**-8.0%-p.**)
Grid reliance	+90.0%
COGEN + BOP efficiencies	
Net electric + heat	61.5%
Net electric	3.3%
Net heat	58.2%
COGEN efficiencies	
Net electric + heat	75.2%
Net electric	6.2%
Gross heat	68.9%
Net heat	68.9%
COGEN heat dump/output	0.0%



CASE SE 620 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

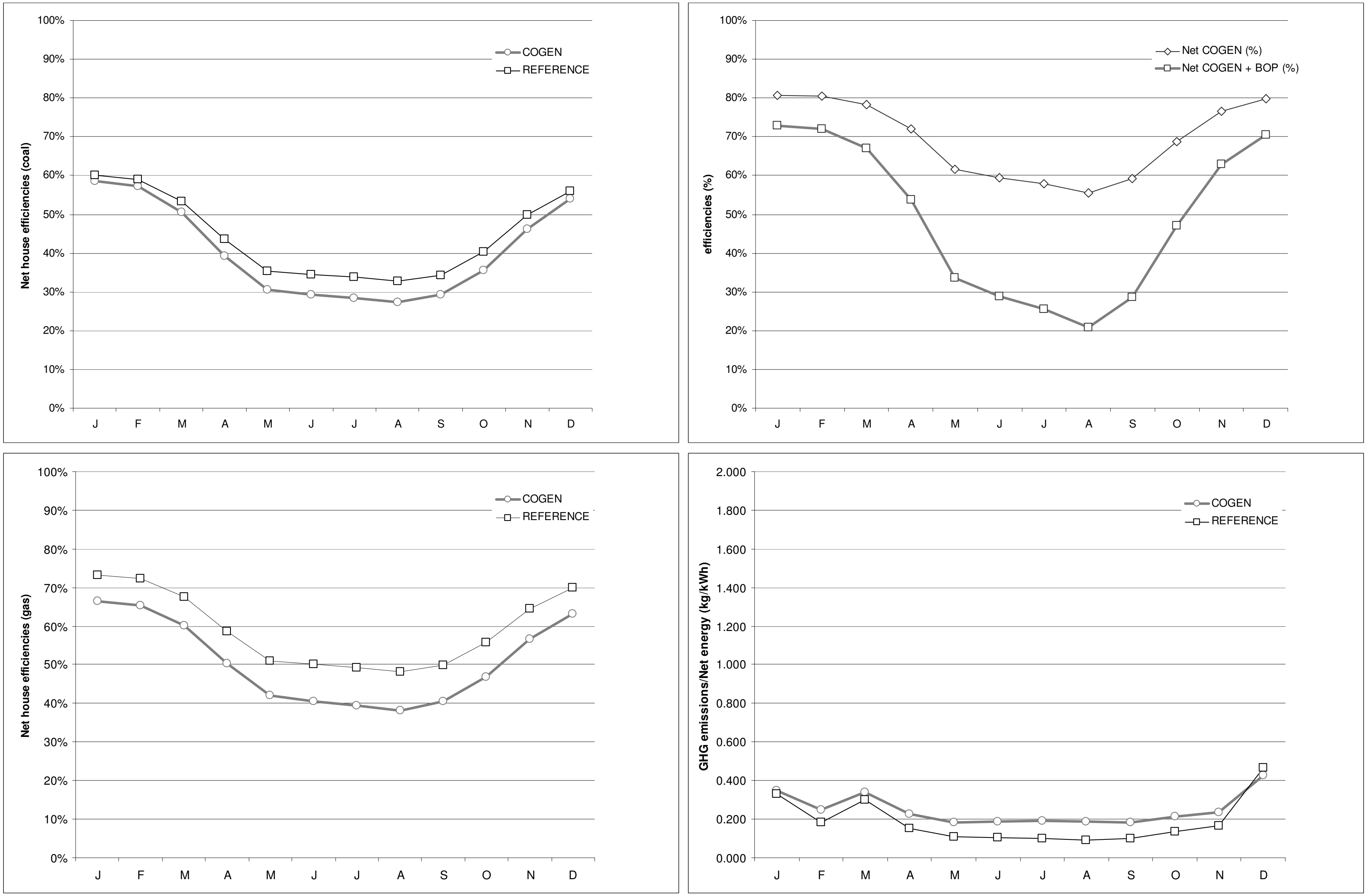
CASE ***SE 810 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Montreal CWEC



Annual summaries

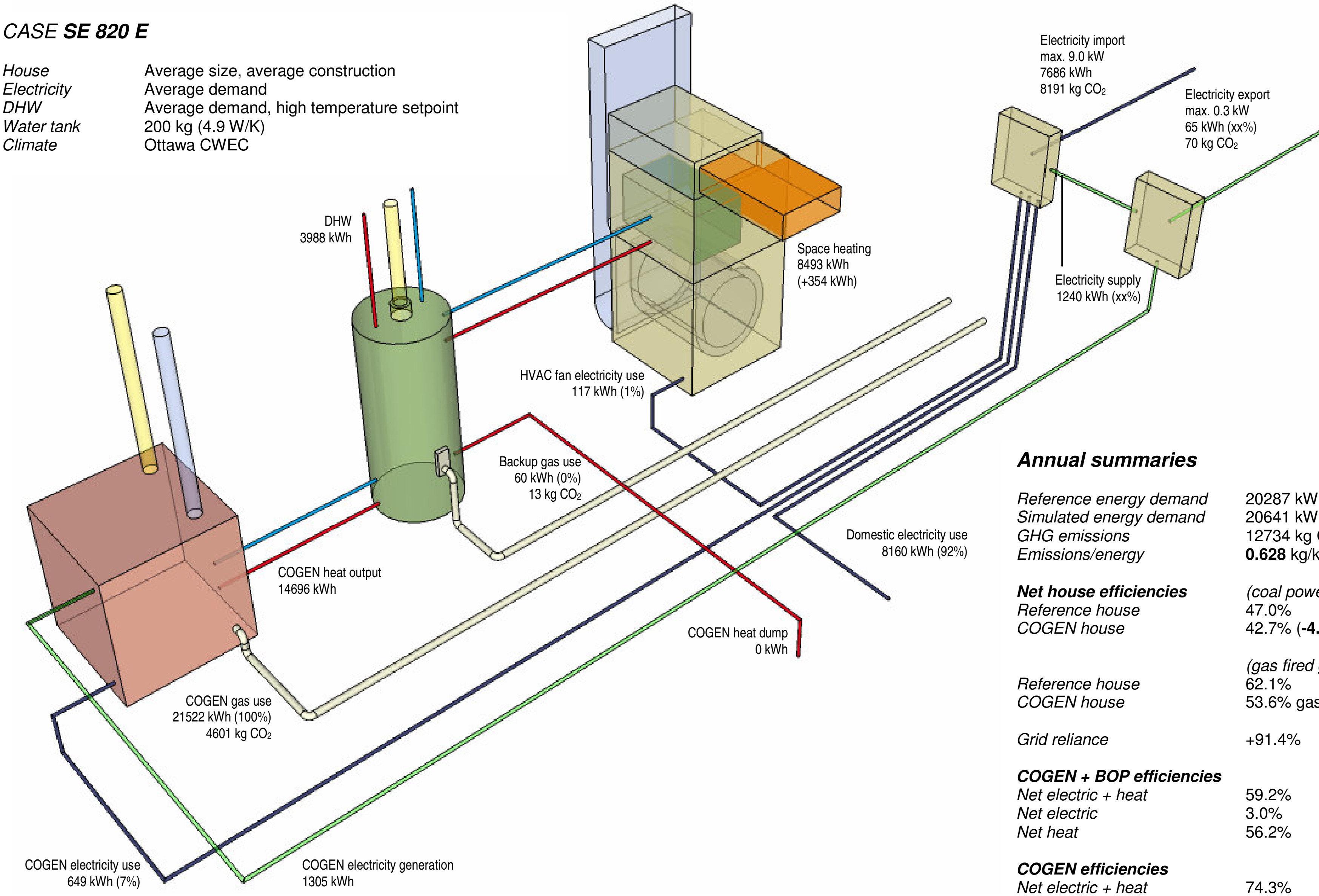
Reference energy demand	20528 kWh
Simulated energy demand	20883 kWh (**+1.7%**)
GHG emissions	5863 kg CO_2 (**+21.6%**)
Emissions/energy	**0.286** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.2%
COGEN house	43.0% (**-4.2%-p.**)
	(gas fired grid)
Reference house	62.4%
COGEN house	53.9% gas (**-8.5%-p.**)
Grid reliance	+91.1%
COGEN + BOP efficiencies	
Net electric + heat	59.6%
Net electric	3.1%
Net heat	56.5%
COGEN efficiencies	
Net electric + heat	74.5%
Net electric	6.1%
Gross heat	68.4%
Net heat	68.4%
COGEN heat dump/output	0.0%



CASE SE 810 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

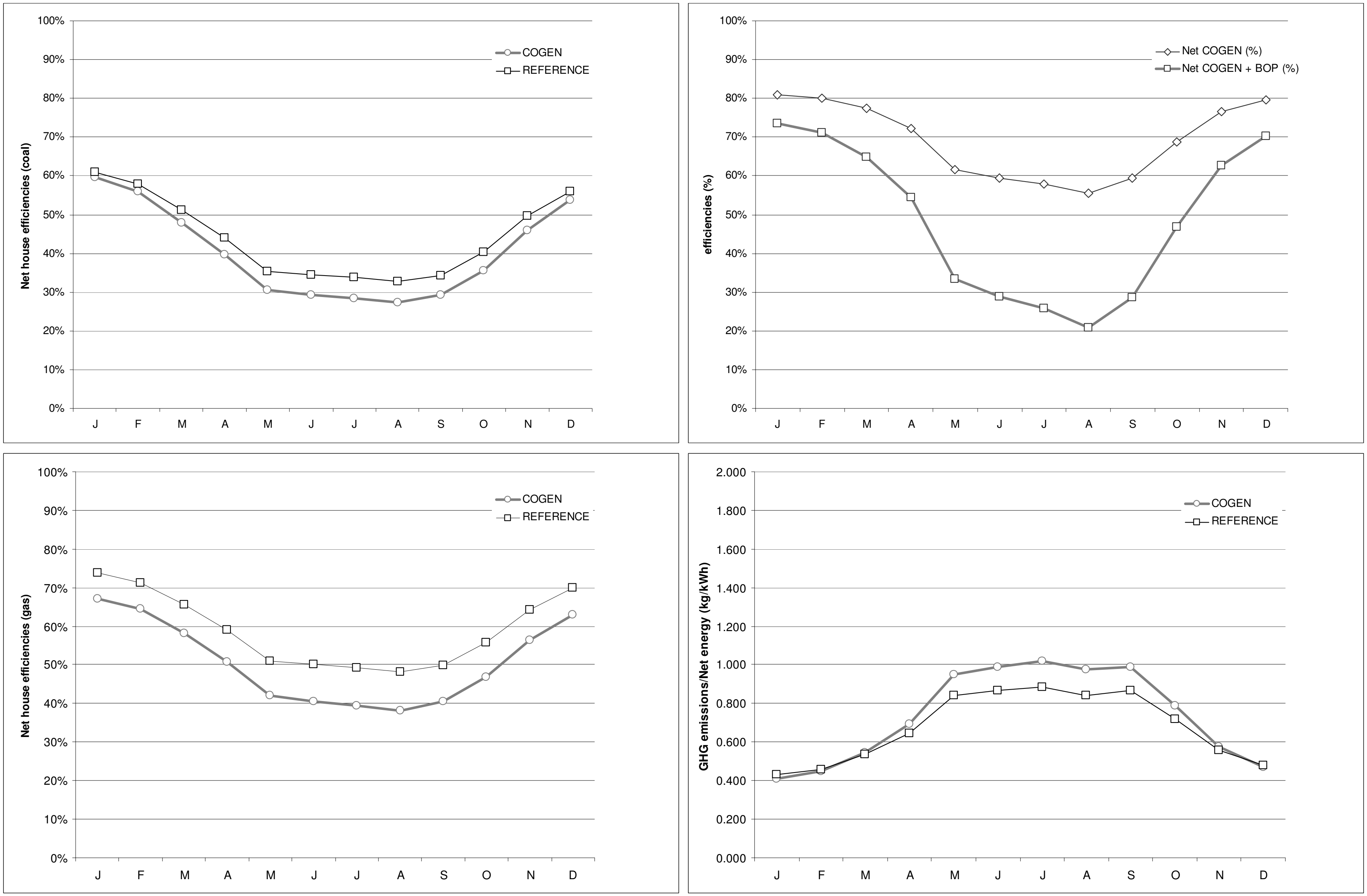
CASE ***SE 820 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa CWEC



Annual summaries

Reference energy demand	20287 kWh
Simulated energy demand	20641 kWh (**+1.7%**)
GHG emissions	12734 kg CO_2 (**+5.4%**)
Emissions/energy	**0.628** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	42.7% (**-4.2%-p.**)
	(gas fired grid)
Reference house	62.1%
COGEN house	53.6% gas (**-8.5%-p.**)
Grid reliance	+91.4%
COGEN + BOP efficiencies	
Net electric + heat	59.2%
Net electric	3.0%
Net heat	56.2%
COGEN efficiencies	
Net electric + heat	74.3%
Net electric	6.1%
Gross heat	68.3%
Net heat	68.3%
COGEN heat dump/output	0.0%

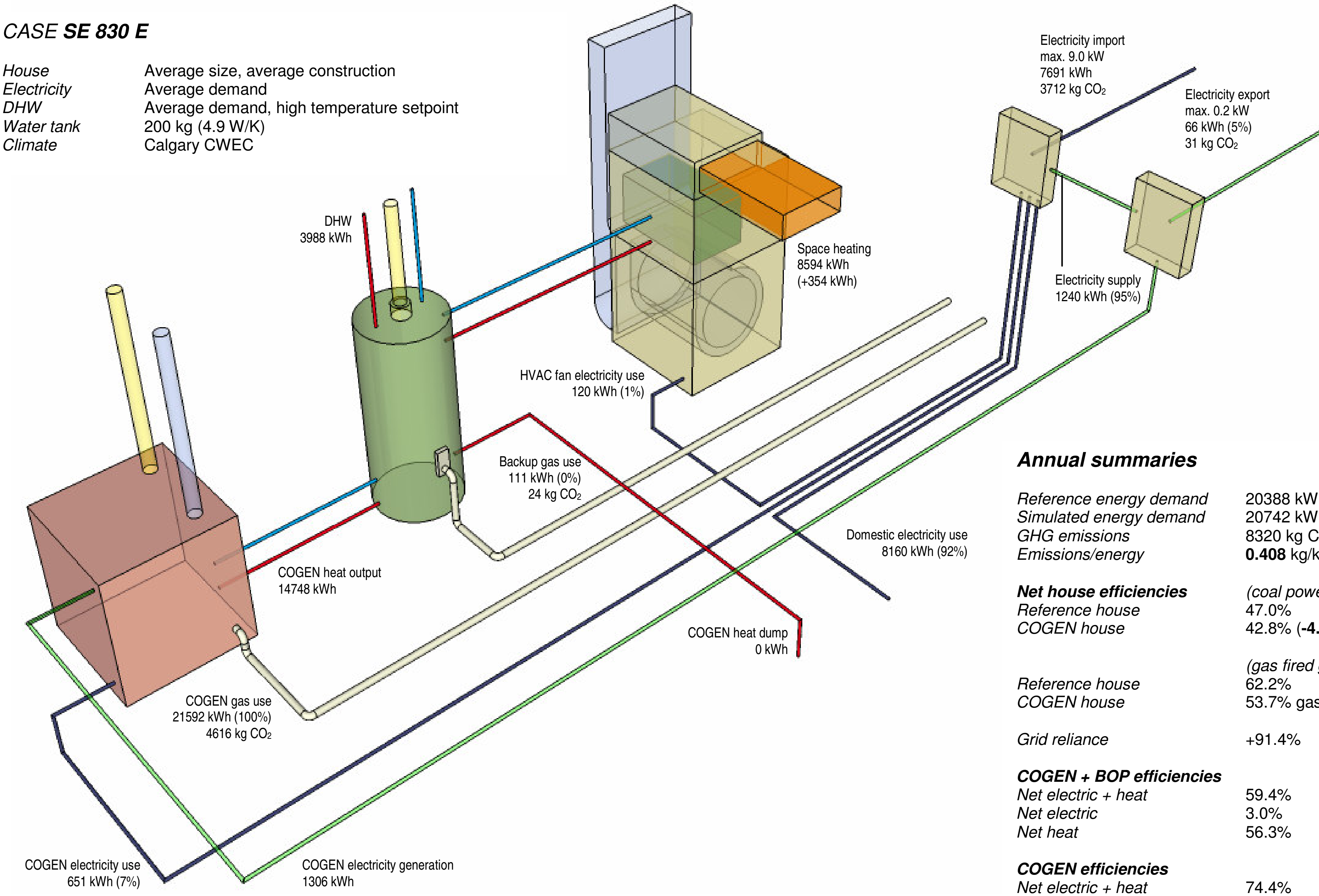


CASE SE 820 E

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

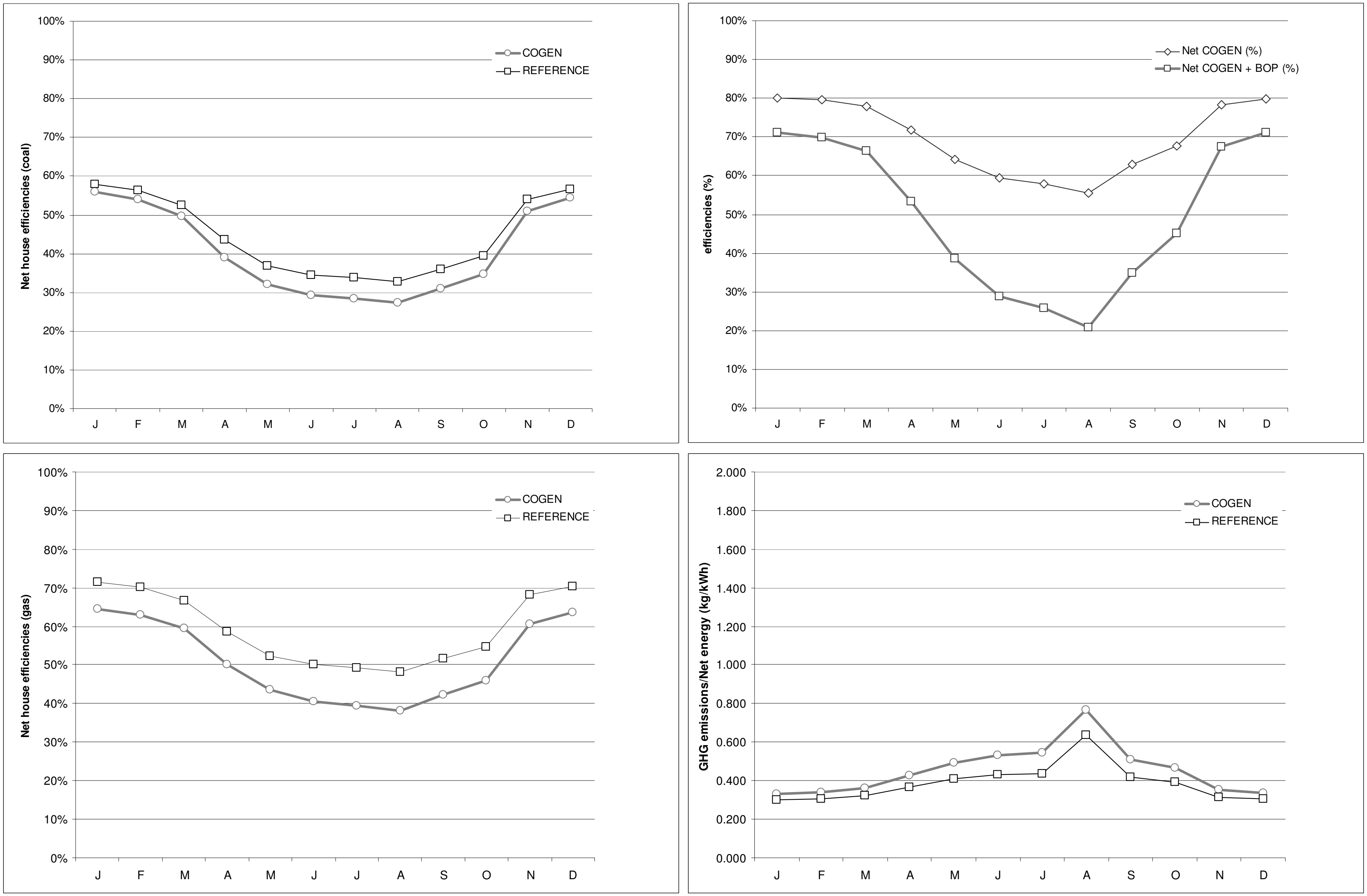
CASE ***SE 830 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Calgary CWEC



Annual summaries

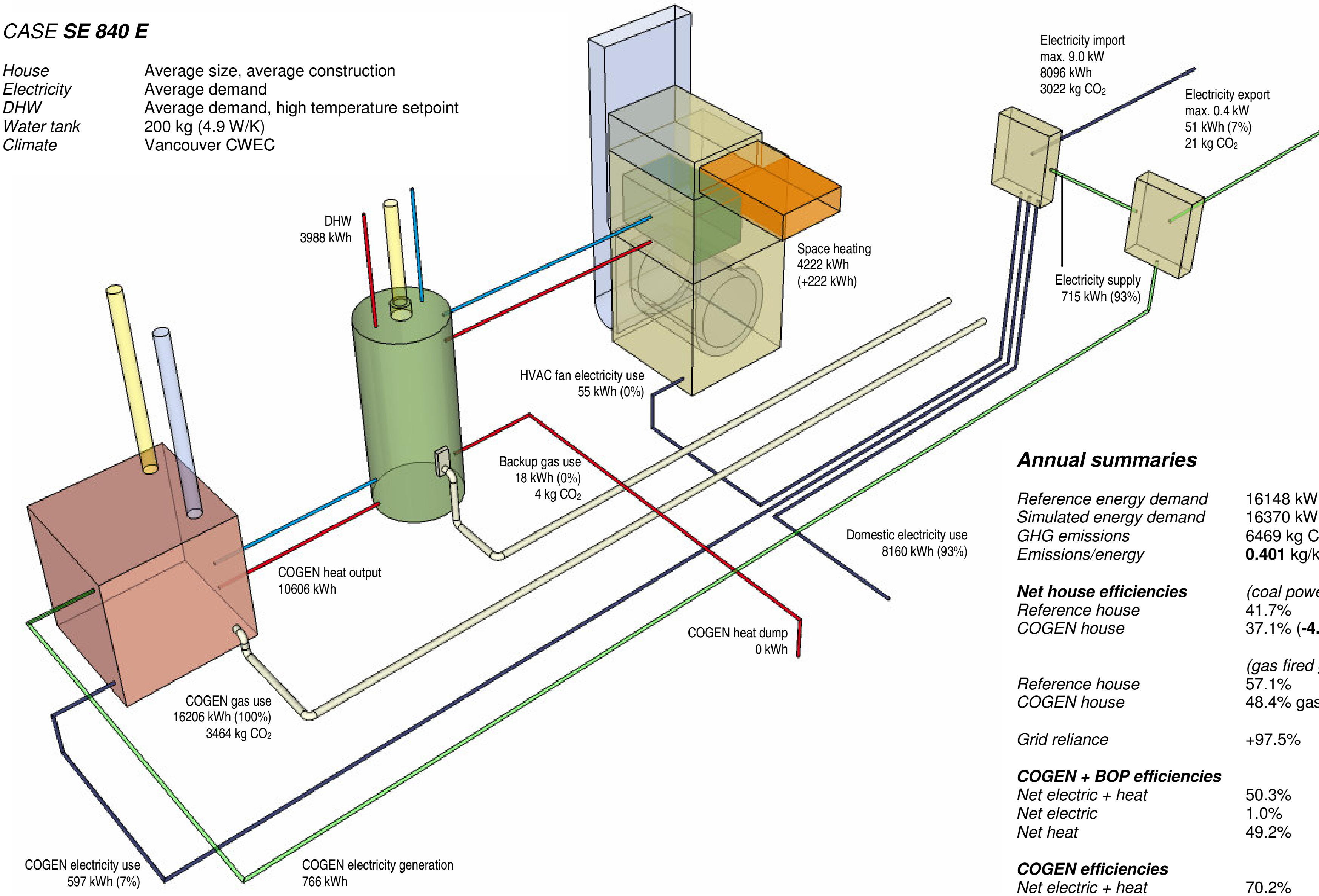
Reference energy demand	20388 kWh
Simulated energy demand	20742 kWh (**+4.3%**)
GHG emissions	8320 kg CO_2 (**+15.4%**)
Emissions/energy	**0.408** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	42.8% (**-4.2%-p.**)
	(gas fired grid)
Reference house	62.2%
COGEN house	53.7% gas (**-8.5%-p.**)
Grid reliance	+91.4%
COGEN + BOP efficiencies	
Net electric + heat	59.4%
Net electric	3.0%
Net heat	56.3%
COGEN efficiencies	
Net electric + heat	74.4%
Net electric	6.1%
Gross heat	68.3%
Net heat	68.3%
COGEN heat dump/output	0.0%



CASE SE 830 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

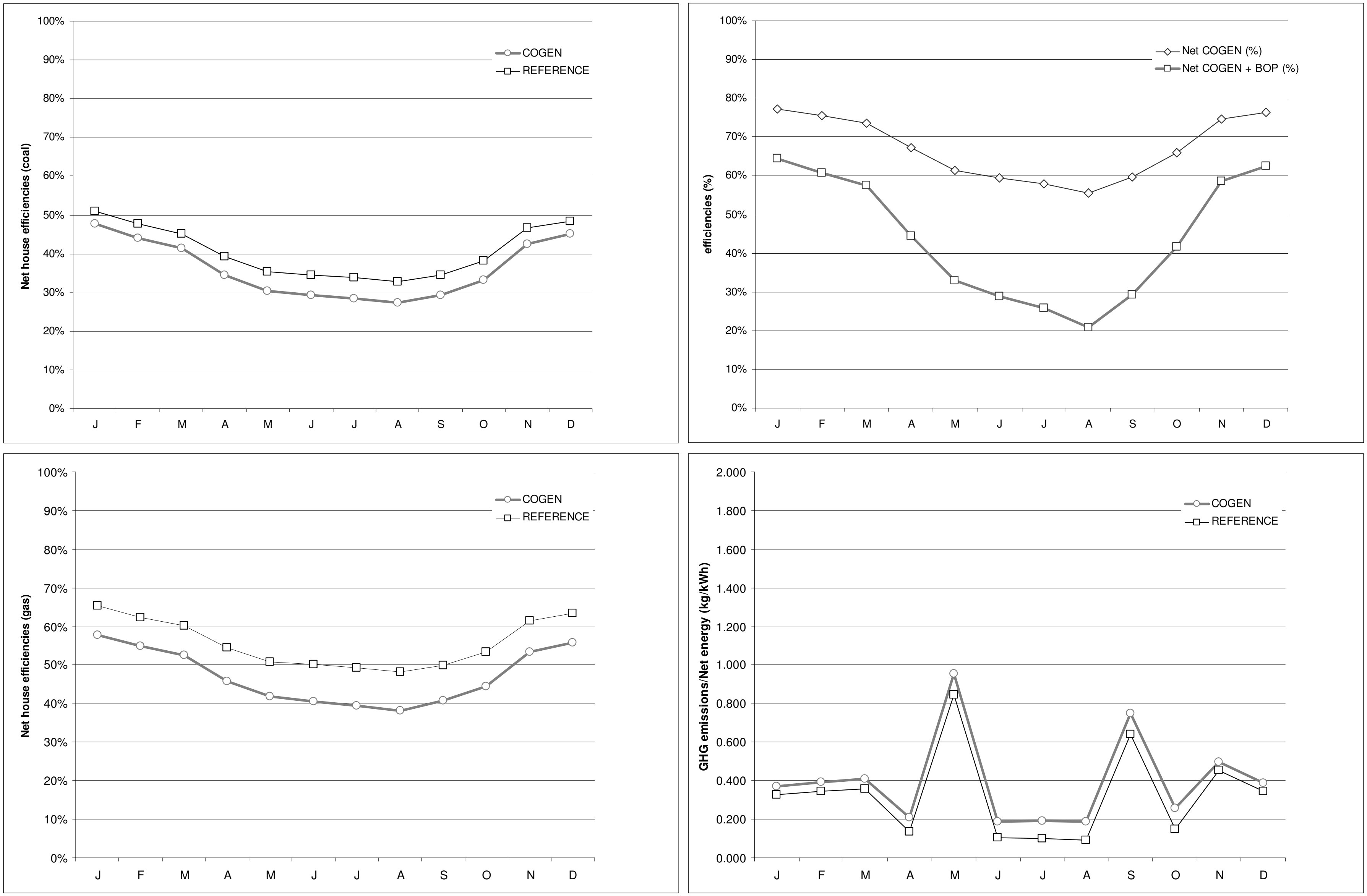
CASE ***SE 840 E***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Vancouver CWEC



Annual summaries

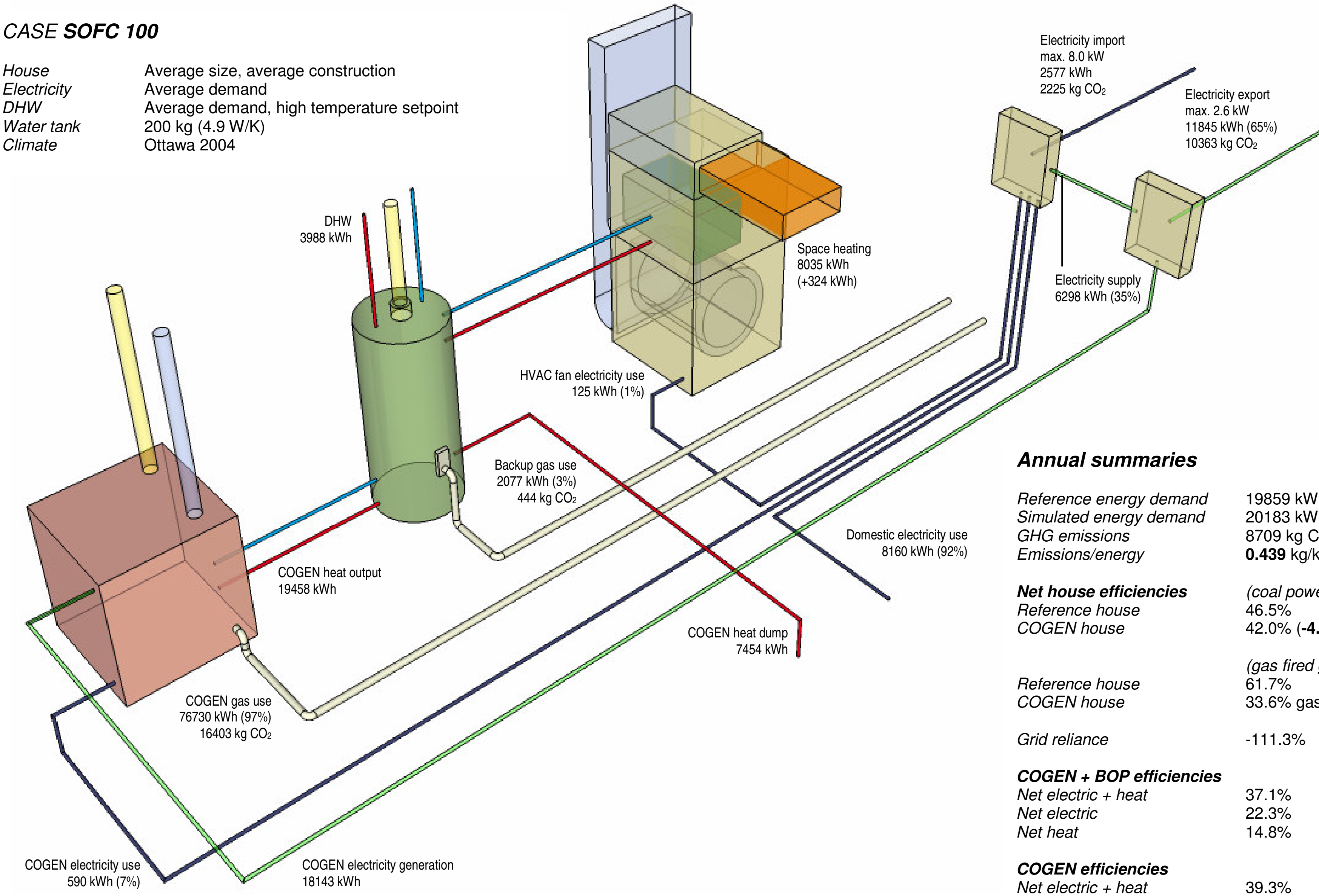
Reference energy demand	16148 kWh
Simulated energy demand	16370 kWh (**+1.4%**)
GHG emissions	6469 kg CO_2 (**+19.3%**)
Emissions/energy	**0.401** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	41.7%
COGEN house	37.1% (**-4.6%-p.**)
	(gas fired grid)
Reference house	57.1%
COGEN house	48.4% gas (**-8.7%-p.**)
Grid reliance	+97.5%
COGEN + BOP efficiencies	
Net electric + heat	50.3%
Net electric	1.0%
Net heat	49.2%
COGEN efficiencies	
Net electric + heat	70.2%
Net electric	4.7%
Gross heat	65.4%
Net heat	65.4%
COGEN heat dump/output	0.0%



CASE SE 840 E *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

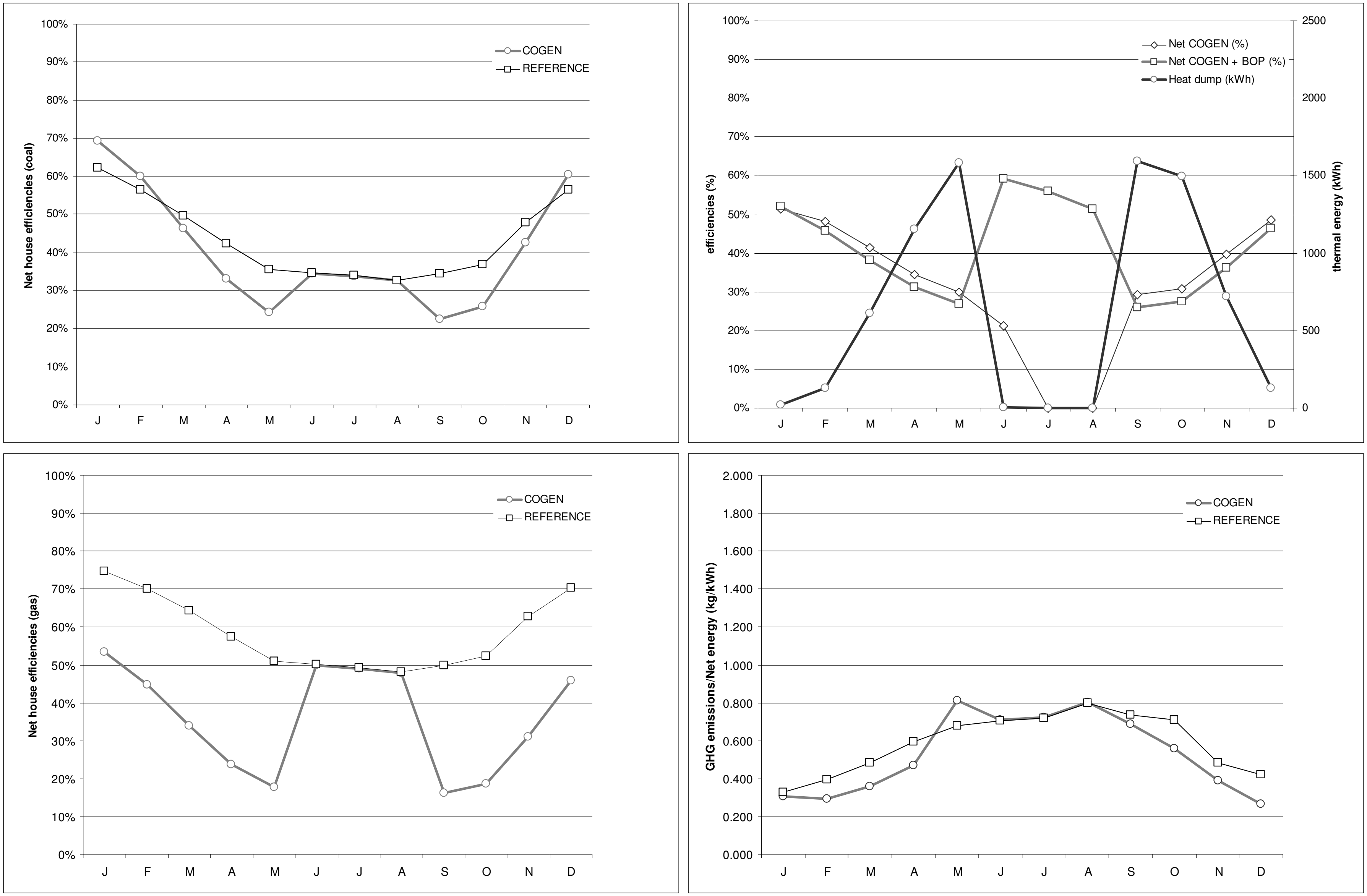
CASE ***SOFC 100***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20183 kWh (**+1.6%**)
GHG emissions	8709 kg CO_2 (**-14.3%**)
Emissions/energy	**0.439** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	42.0% (**-4.5%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	33.6% gas (**-28.1%-p.**)
Grid reliance	-111.3%
COGEN + BOP efficiencies	
Net electric + heat	37.1%
Net electric	22.3%
Net heat	14.8%
COGEN efficiencies	
Net electric + heat	39.3%
Net electric	23.6%
Gross heat	25.4%
Net heat	15.6%
COGEN heat dump/output	38.3%

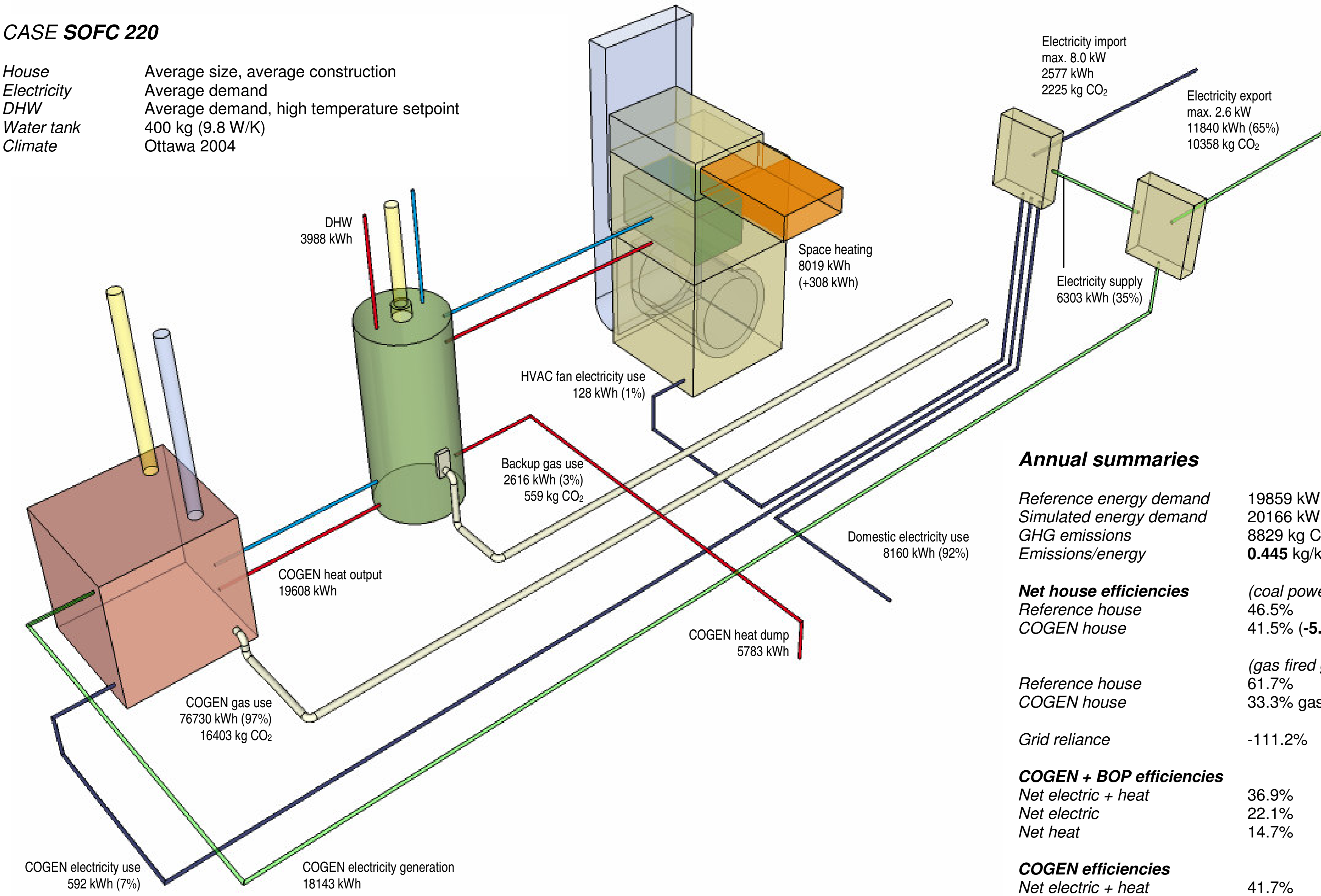


CASE SOFC 100

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

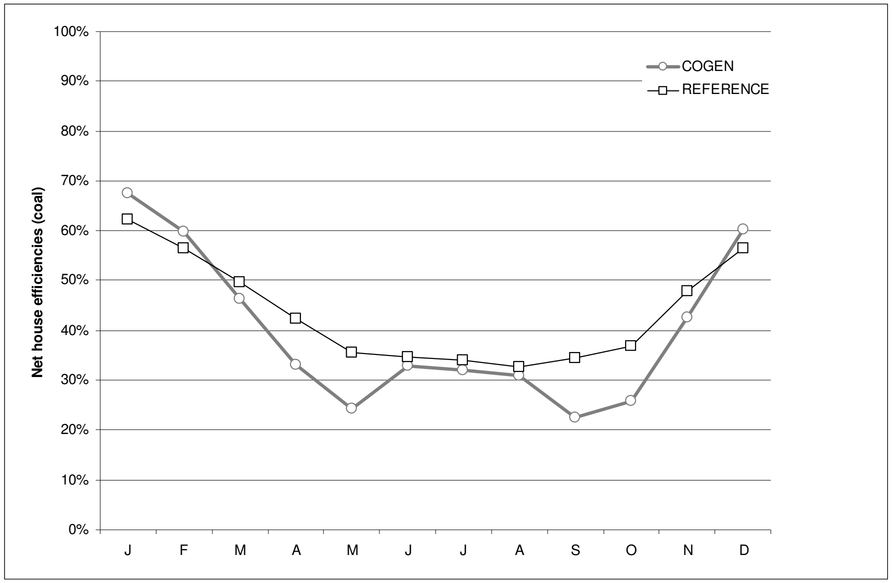
CASE ***SOFC 220***

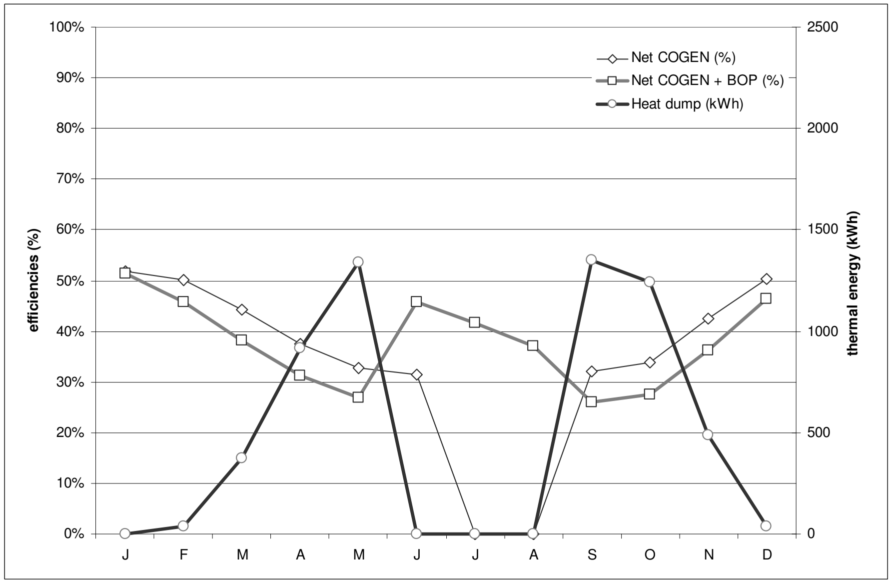
House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	400 kg (9.8 W/K)
Climate	Ottawa 2004

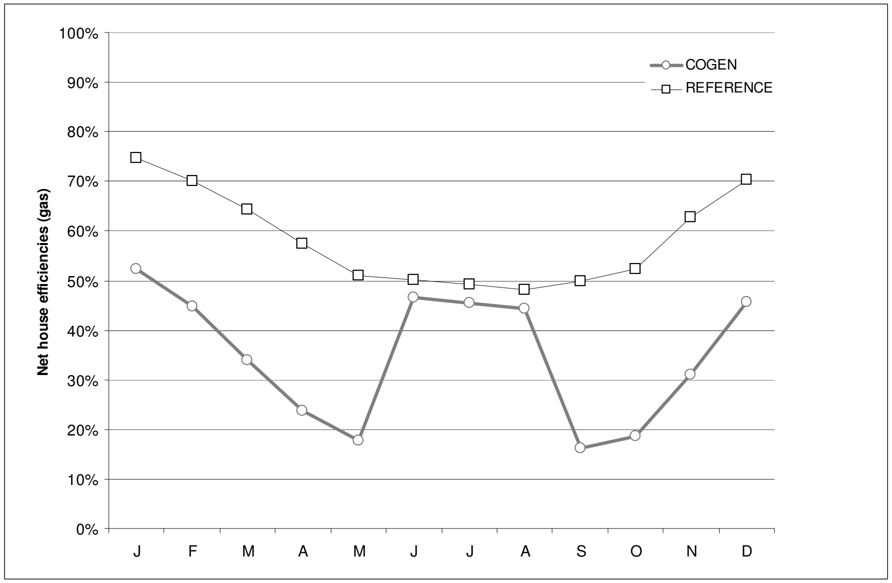


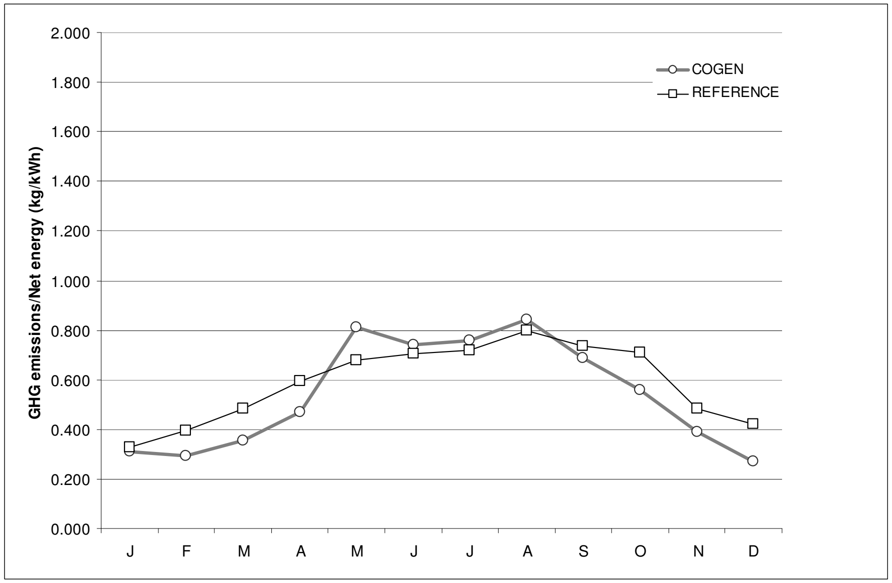
Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20166 kWh (**+1.5%**)
GHG emissions	8829 kg CO_2 (**-13.1%**)
Emissions/energy	**0.445** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	41.5% (**-5.0%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	33.3% gas (**-28.4%-p.**)
Grid reliance	-111.2%
COGEN + BOP efficiencies	
Net electric + heat	36.9%
Net electric	22.1%
Net heat	14.7%
COGEN efficiencies	
Net electric + heat	41.7%
Net electric	23.6%
Gross heat	25.6%
Net heat	18.0%
COGEN heat dump/output	29.5%







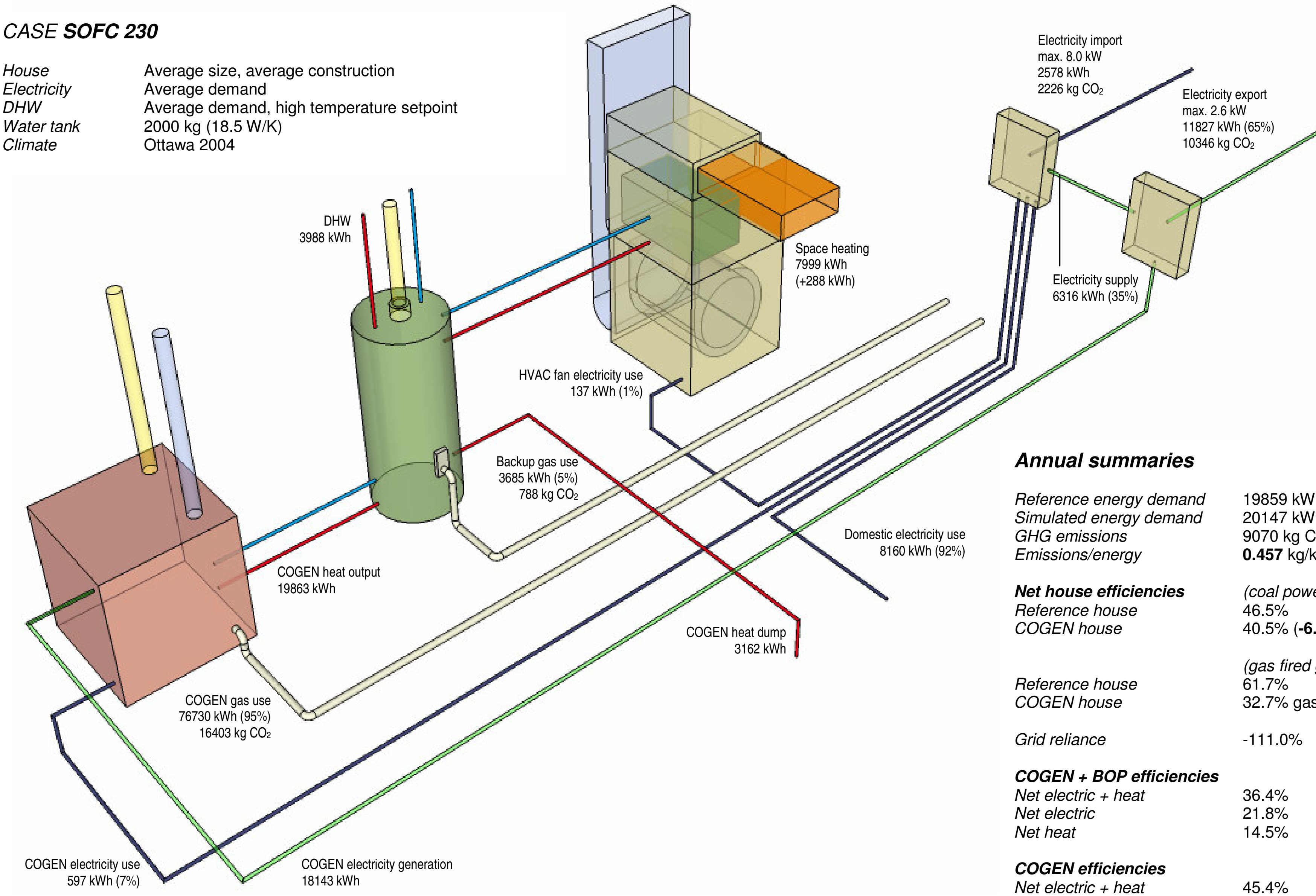


CASE SOFC 220

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

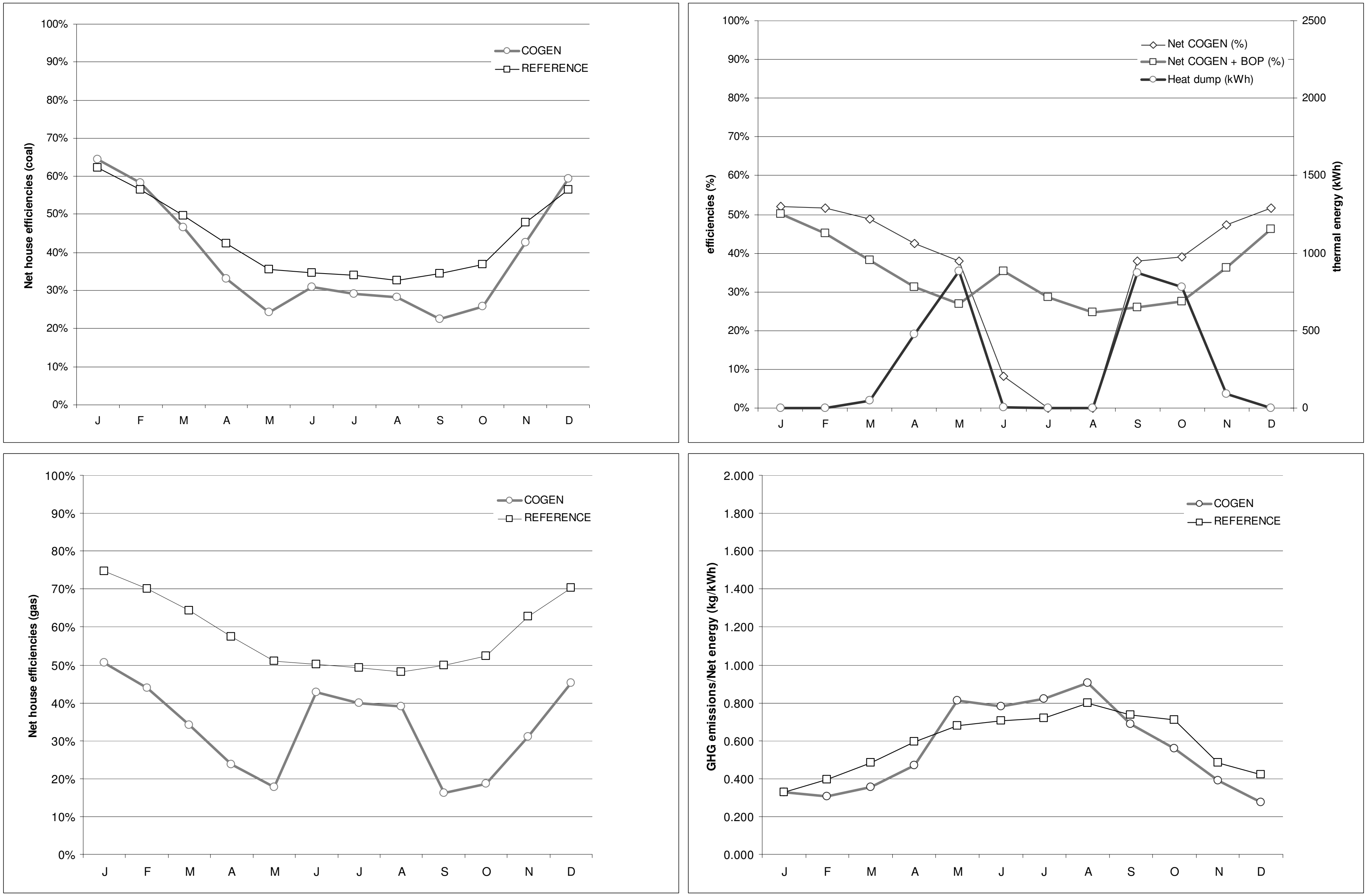
CASE ***SOFC 230***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	2000 kg (18.5 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20147 kWh (**+1.4%**)
GHG emissions	9070 kg CO_2 (**-10.7%**)
Emissions/energy	**0.457** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	40.5% (**-6.0%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	32.7% gas (**-29.0%-p.**)
Grid reliance	-111.0%
COGEN + BOP efficiencies	
Net electric + heat	36.4%
Net electric	21.8%
Net heat	14.5%
COGEN efficiencies	
Net electric + heat	45.4%
Net electric	23.6%
Gross heat	25.9%
Net heat	21.8%
COGEN heat dump/output	15.9%

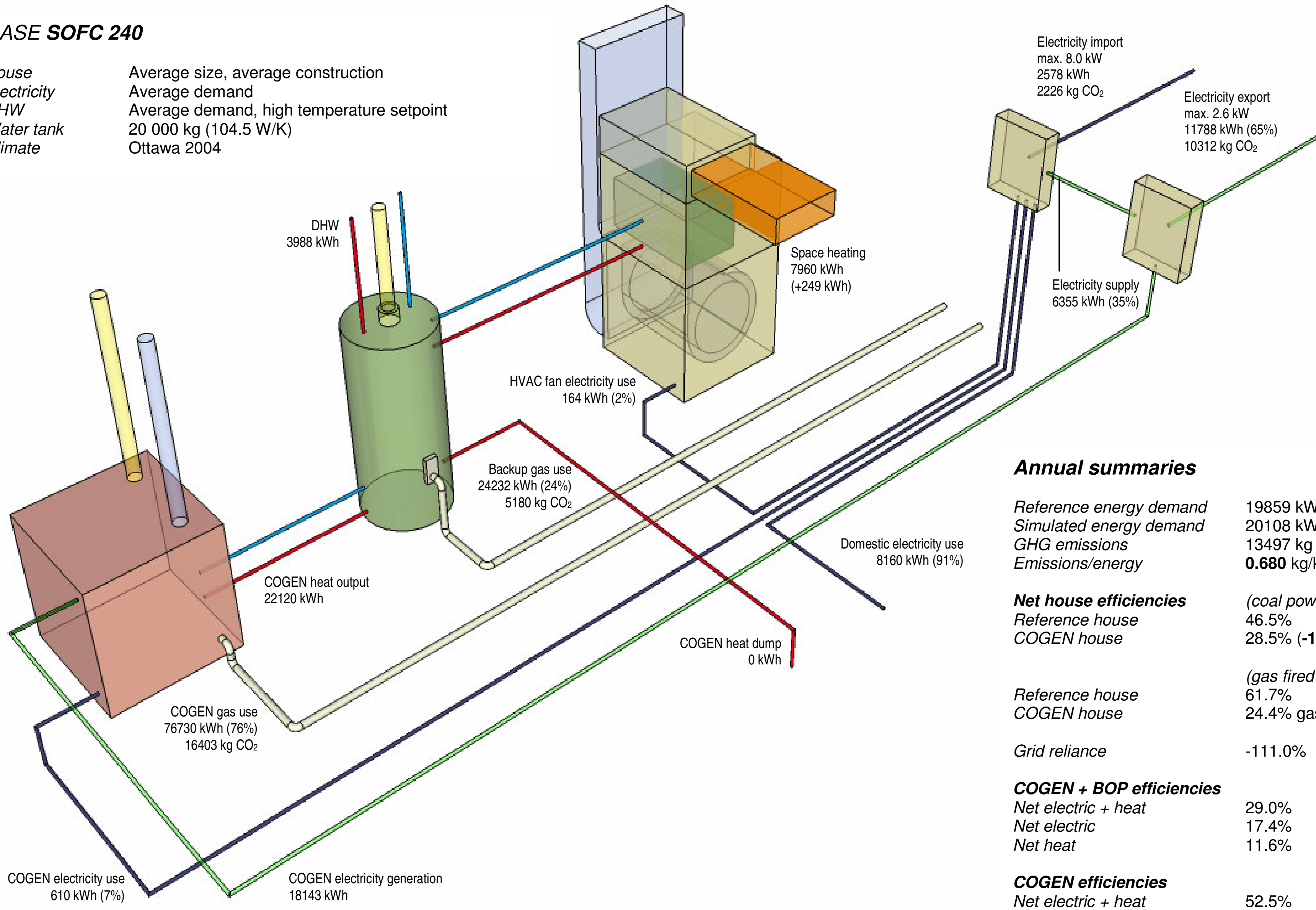


CASE SOFC 230

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

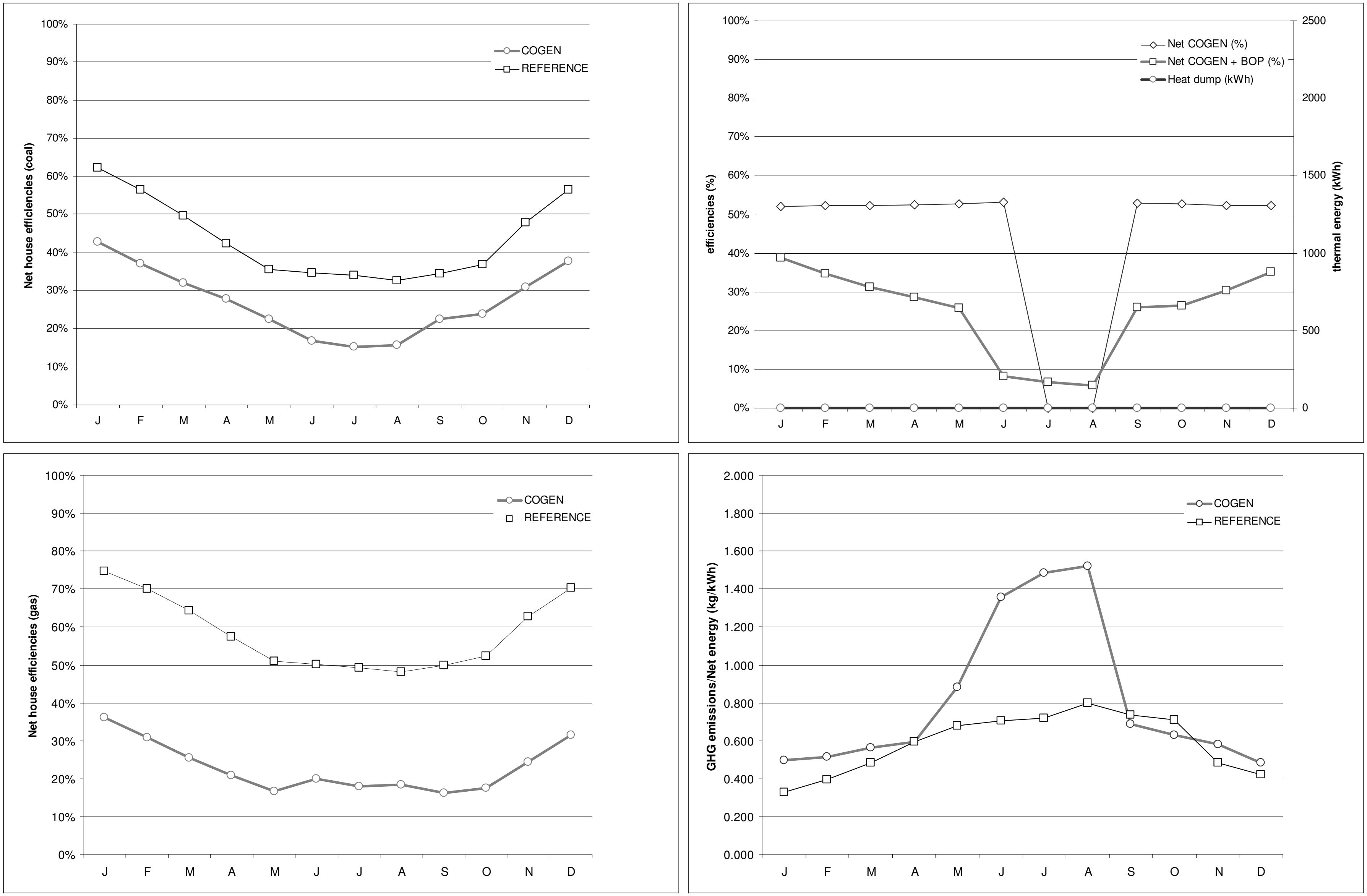
CASE ***SOFC 240***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	20 000 kg (104.5 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20108 kWh (**+1.3%**)
GHG emissions	13497 kg CO_2 (**+32.9%**)
Emissions/energy	**0.680** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	28.5% (**-18.0%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	24.4% gas (**-37.3%-p.**)
Grid reliance	-111.0%
COGEN + BOP efficiencies	
Net electric + heat	29.0%
Net electric	17.4%
Net heat	11.6%
COGEN efficiencies	
Net electric + heat	52.5%
Net electric	23.6%
Gross heat	28.8%
Net heat	28.8%
COGEN heat dump/output	0.0%

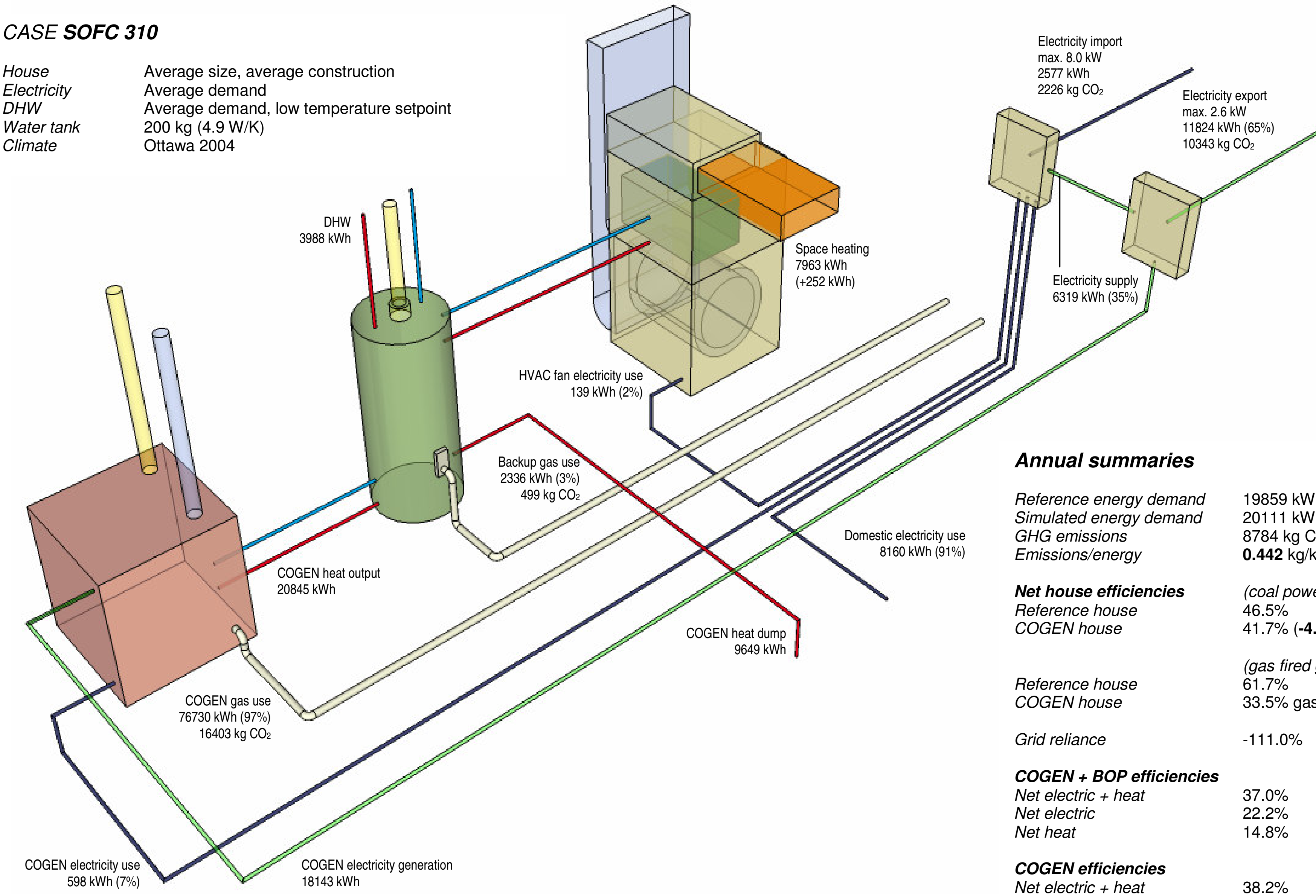


CASE SOFC 240

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

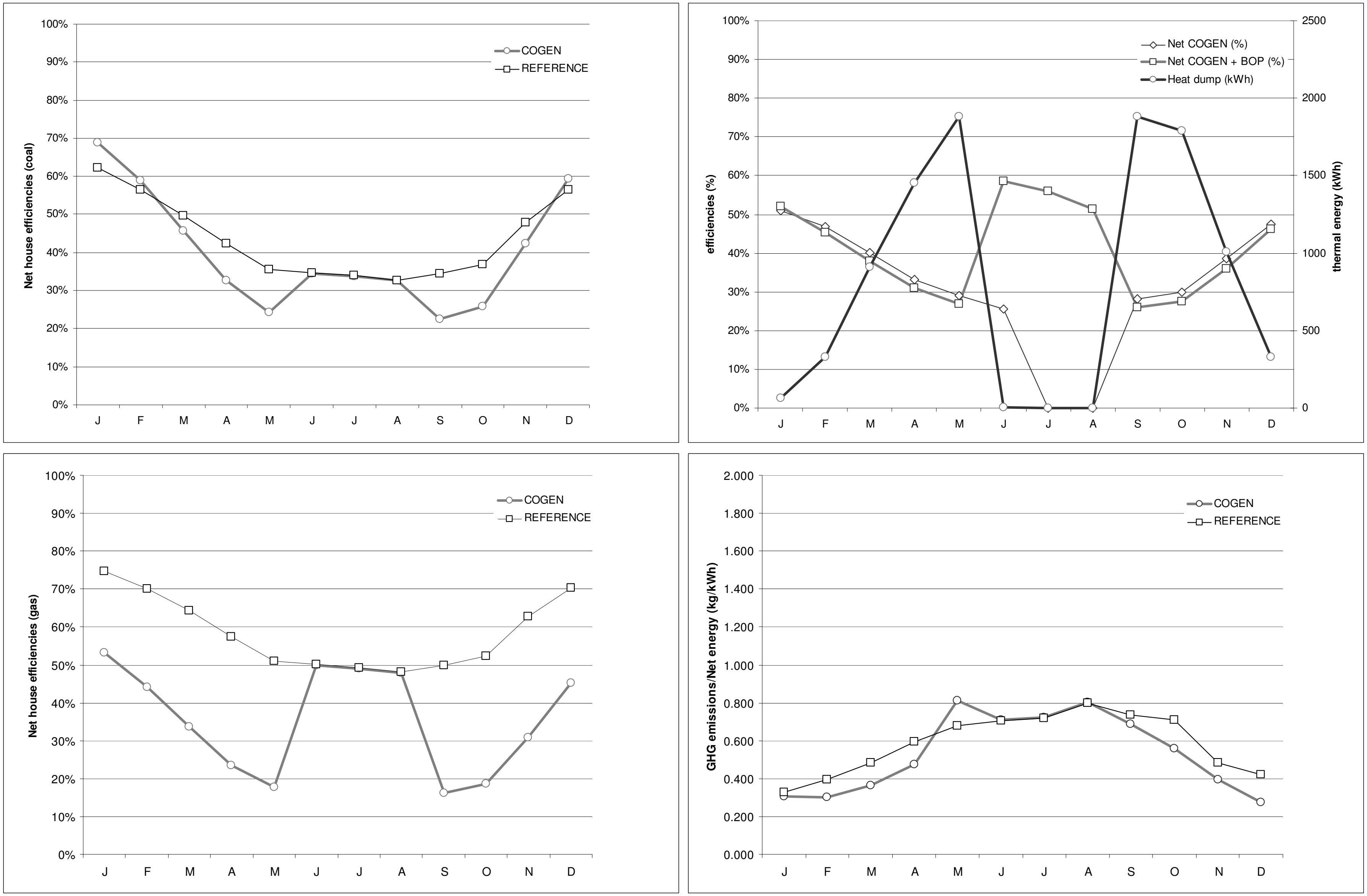
CASE ***SOFC 310***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, low temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	19859 kWh
Simulated energy demand	20111 kWh (**+1.3%**)
GHG emissions	8784 kg CO_2 (**-13.5%**)
Emissions/energy	**0.442** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	41.7% (**-4.8%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	33.5% gas (**-28.2%-p.**)
Grid reliance	-111.0%
COGEN + BOP efficiencies	
Net electric + heat	37.0%
Net electric	22.2%
Net heat	14.8%
COGEN efficiencies	
Net electric + heat	38.2%
Net electric	23.6%
Gross heat	27.2%
Net heat	14.6%
COGEN heat dump/output	46.3%

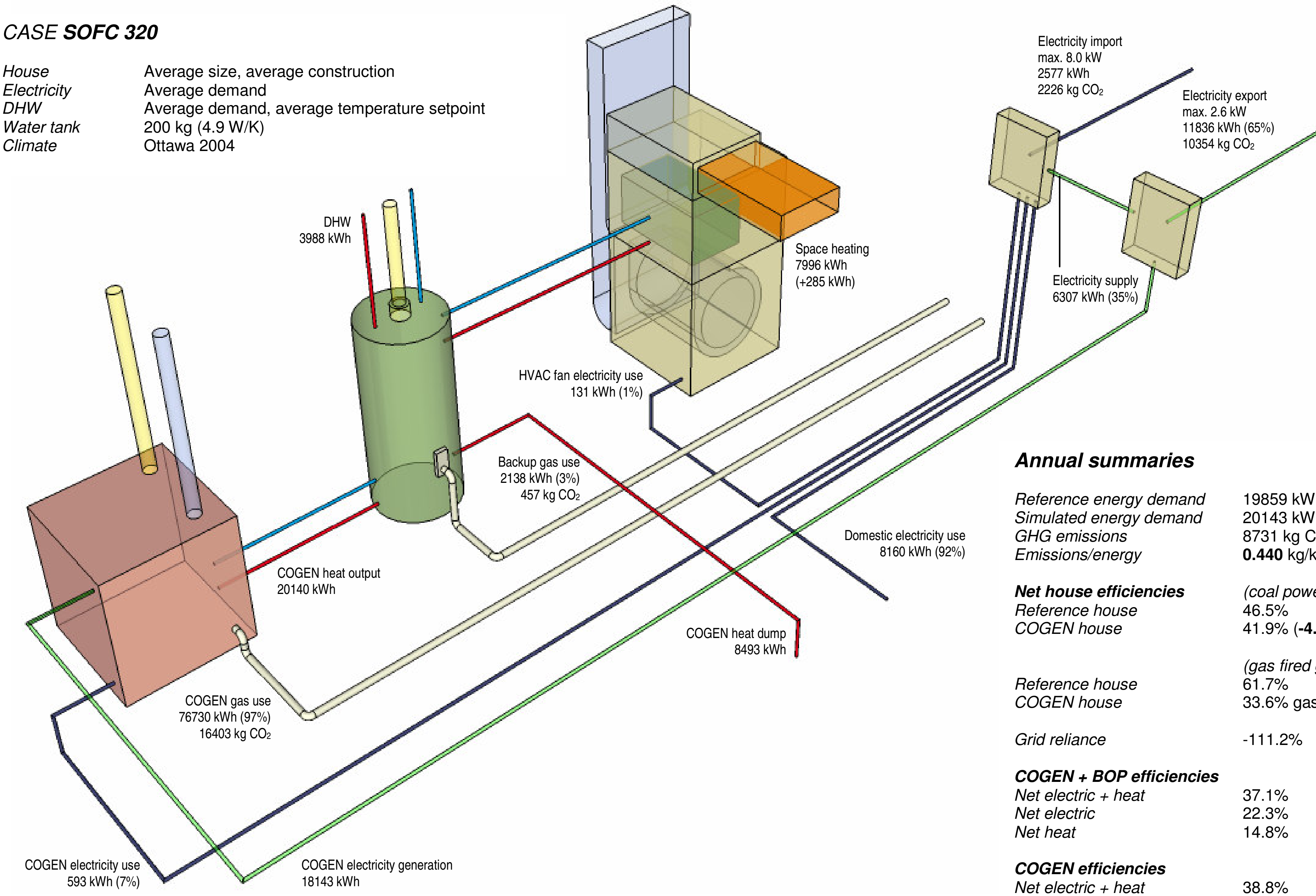


CASE SOFC 310

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

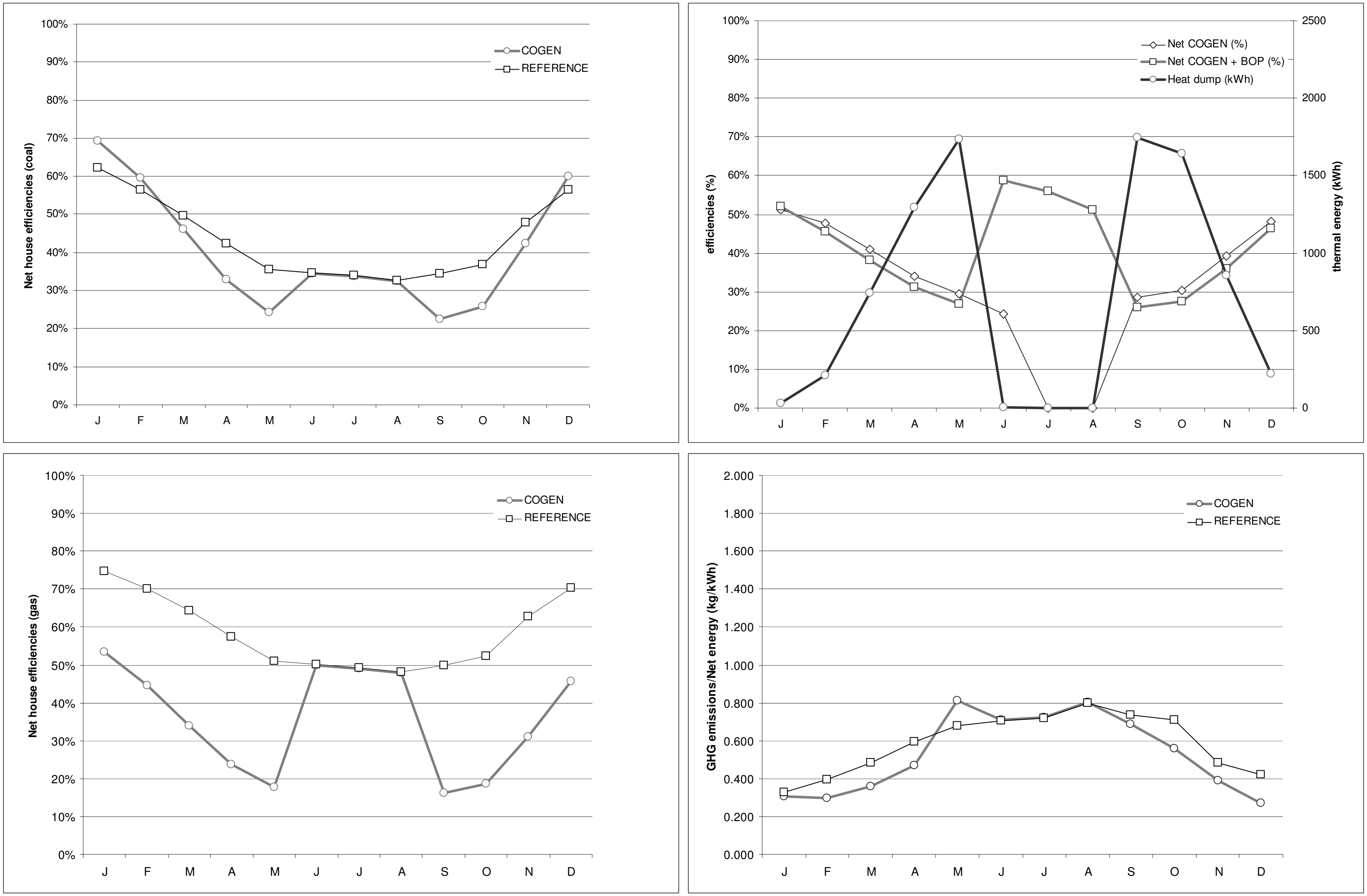
CASE ***SOFC 320***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, average temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

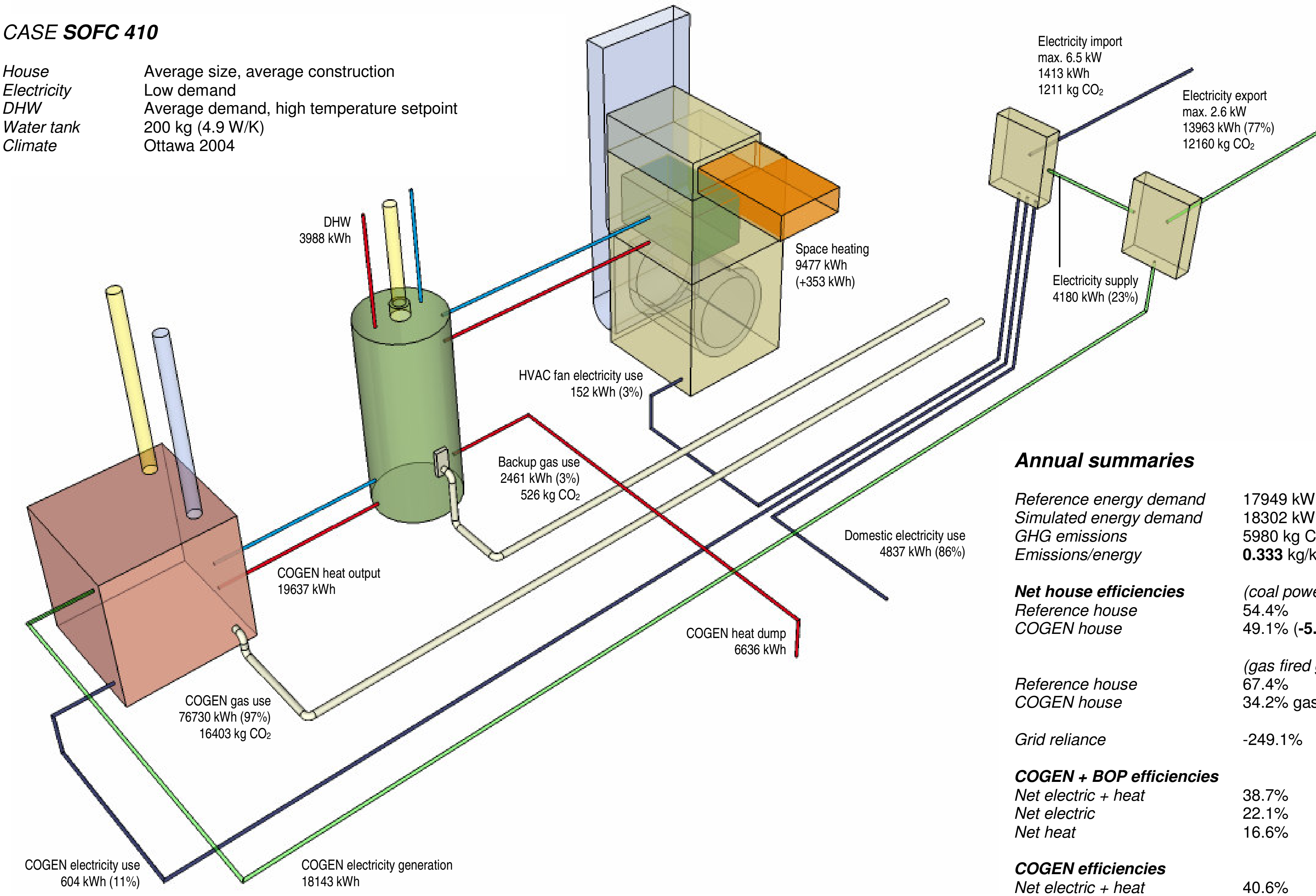
Reference energy demand	19859 kWh
Simulated energy demand	20143 kWh (**+1.4%**)
GHG emissions	8731 kg CO_2 (**-14.0%**)
Emissions/energy	**0.440** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.5%
COGEN house	41.9% (**-4.6%-p.**)
	(gas fired grid)
Reference house	61.7%
COGEN house	33.6% gas (**-28.1%-p.**)
Grid reliance	-111.2%
COGEN + BOP efficiencies	
Net electric + heat	37.1%
Net electric	22.3%
Net heat	14.8%
COGEN efficiencies	
Net electric + heat	38.8%
Net electric	23.6%
Gross heat	26.2%
Net heat	15.2%
COGEN heat dump/output	42.2%



CASE SOFC 320 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

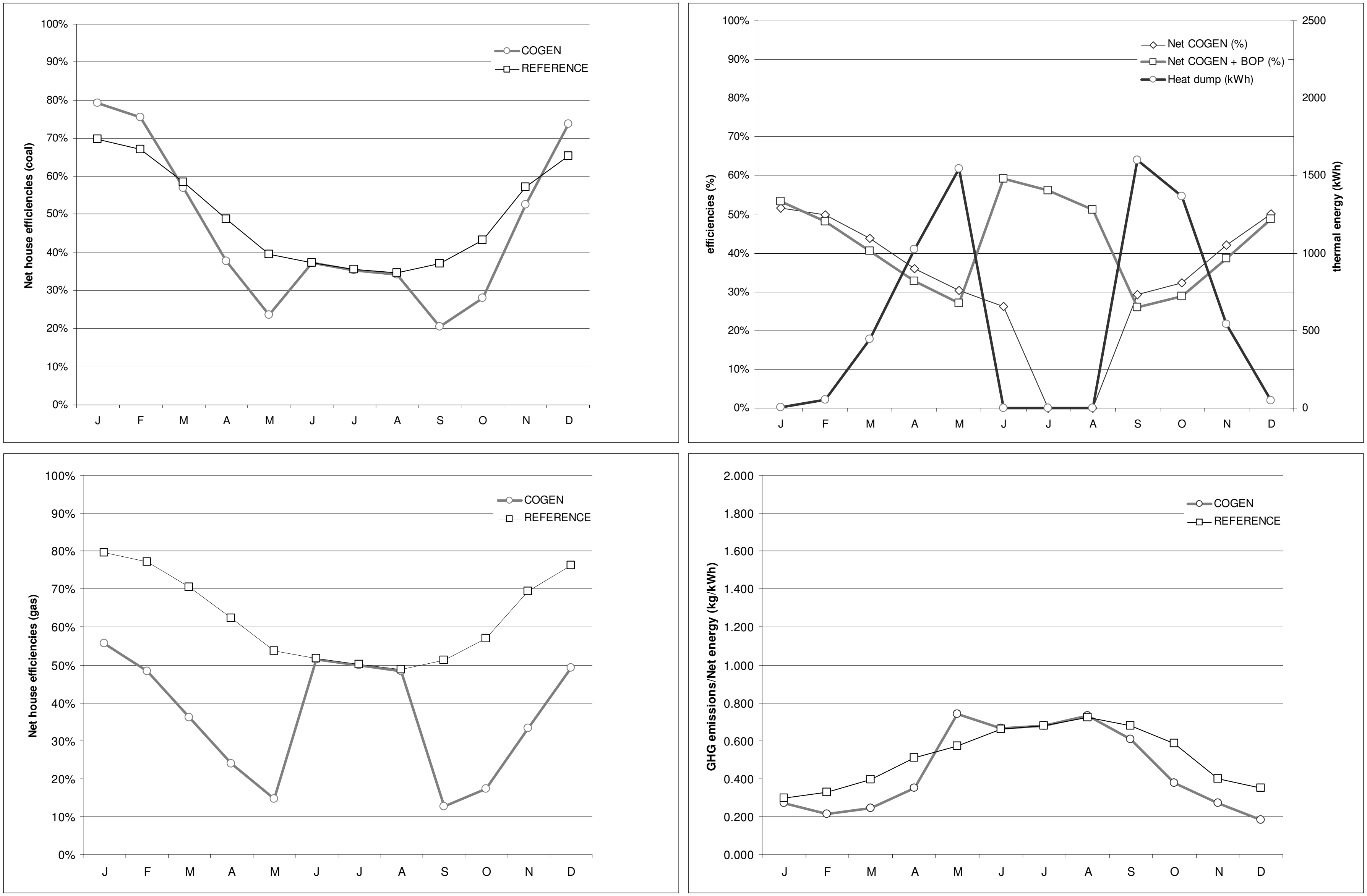
CASE ***SOFC 410***

House	Average size, average construction
Electricity	Low demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

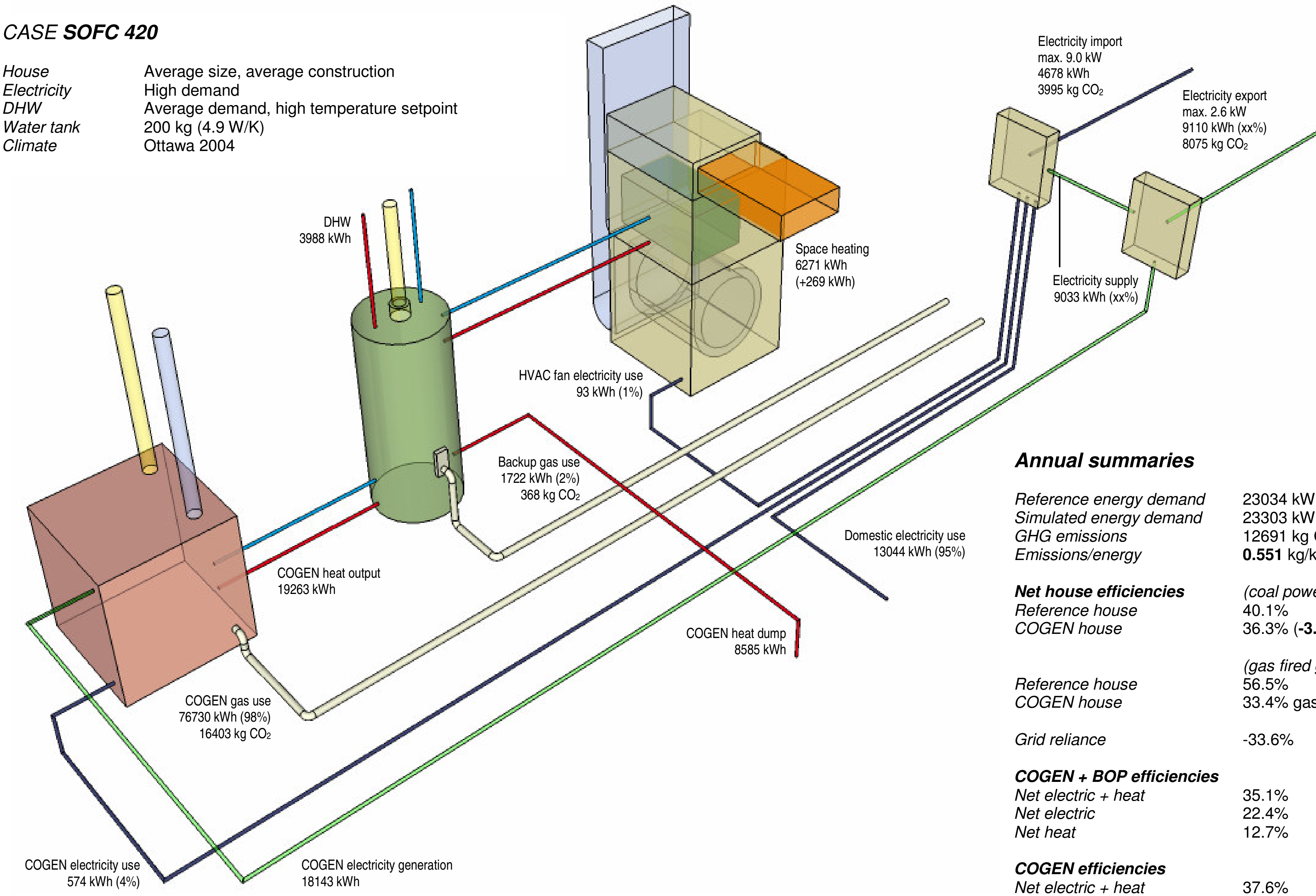
Reference energy demand	17949 kWh
Simulated energy demand	18302 kWh (**+2.0%**)
GHG emissions	5980 kg CO_2 (**-21.8%**)
Emissions/energy	**0.333** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	54.4%
COGEN house	49.1% (**-5.3%-p.**)
	(gas fired grid)
Reference house	67.4%
COGEN house	34.2% gas (**-33.2%-p.**)
Grid reliance	-249.1%
COGEN + BOP efficiencies	
Net electric + heat	38.7%
Net electric	22.1%
Net heat	16.6%
COGEN efficiencies	
Net electric + heat	40.6%
Net electric	23.6%
Gross heat	25.6%
Net heat	16.9%
COGEN heat dump/output	33.8%



CASE SOFC 410 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

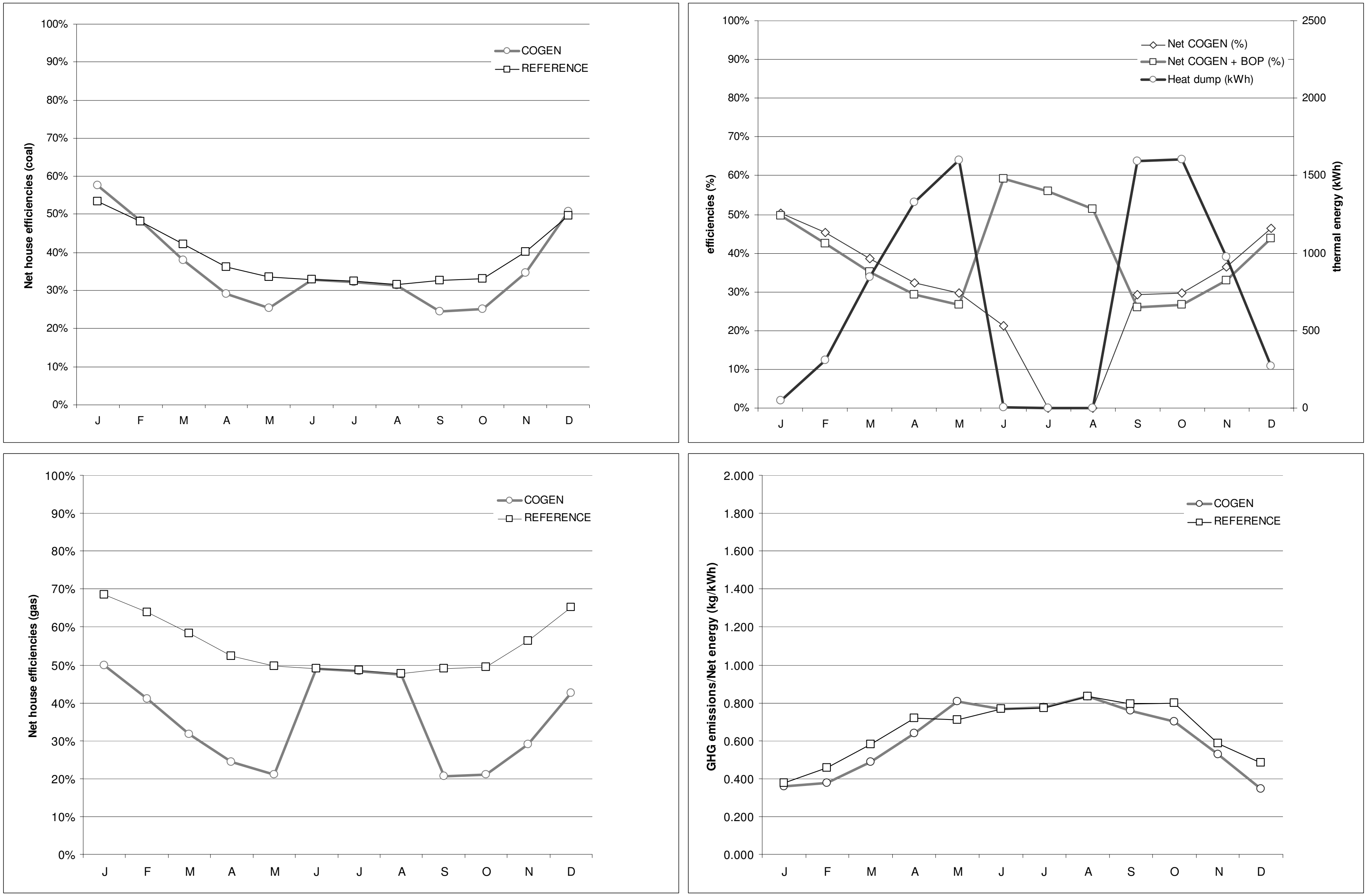
CASE ***SOFC 420***

House	Average size, average construction
Electricity	High demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	23034 kWh
Simulated energy demand	23303 kWh (**+1.2%**)
GHG emissions	12691 kg CO_2 (**-8.3%**)
Emissions/energy	**0.551** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	40.1%
COGEN house	36.3% (**-3.8%-p.**)
	(gas fired grid)
Reference house	56.5%
COGEN house	33.4% gas (**-23.2%-p.**)
Grid reliance	-33.6%
COGEN + BOP efficiencies	
Net electric + heat	35.1%
Net electric	22.4%
Net heat	12.7%
COGEN efficiencies	
Net electric + heat	37.6%
Net electric	23.6%
Gross heat	25.1%
Net heat	13.9%
COGEN heat dump/output	44.6%

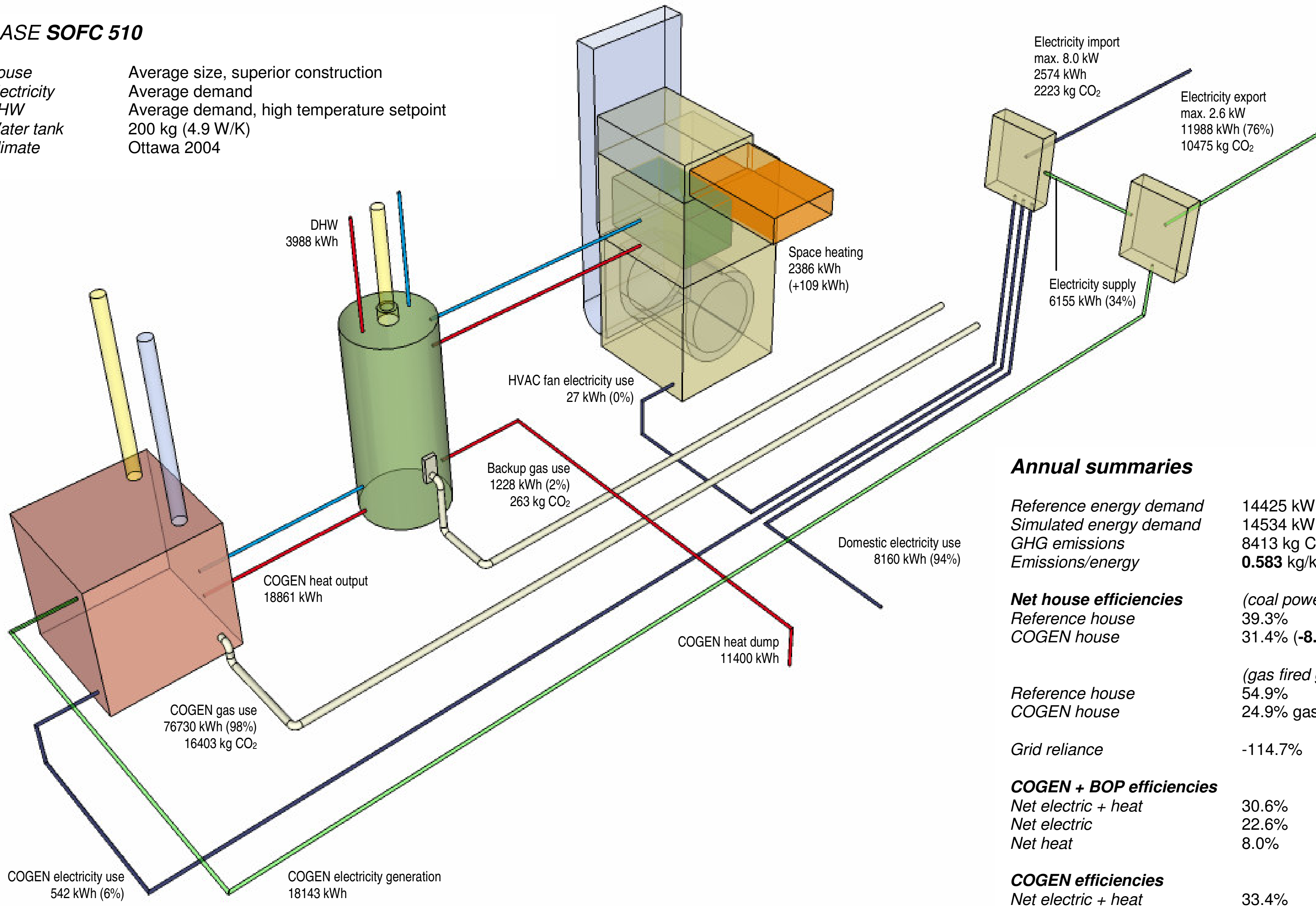


CASE SOFC 420

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

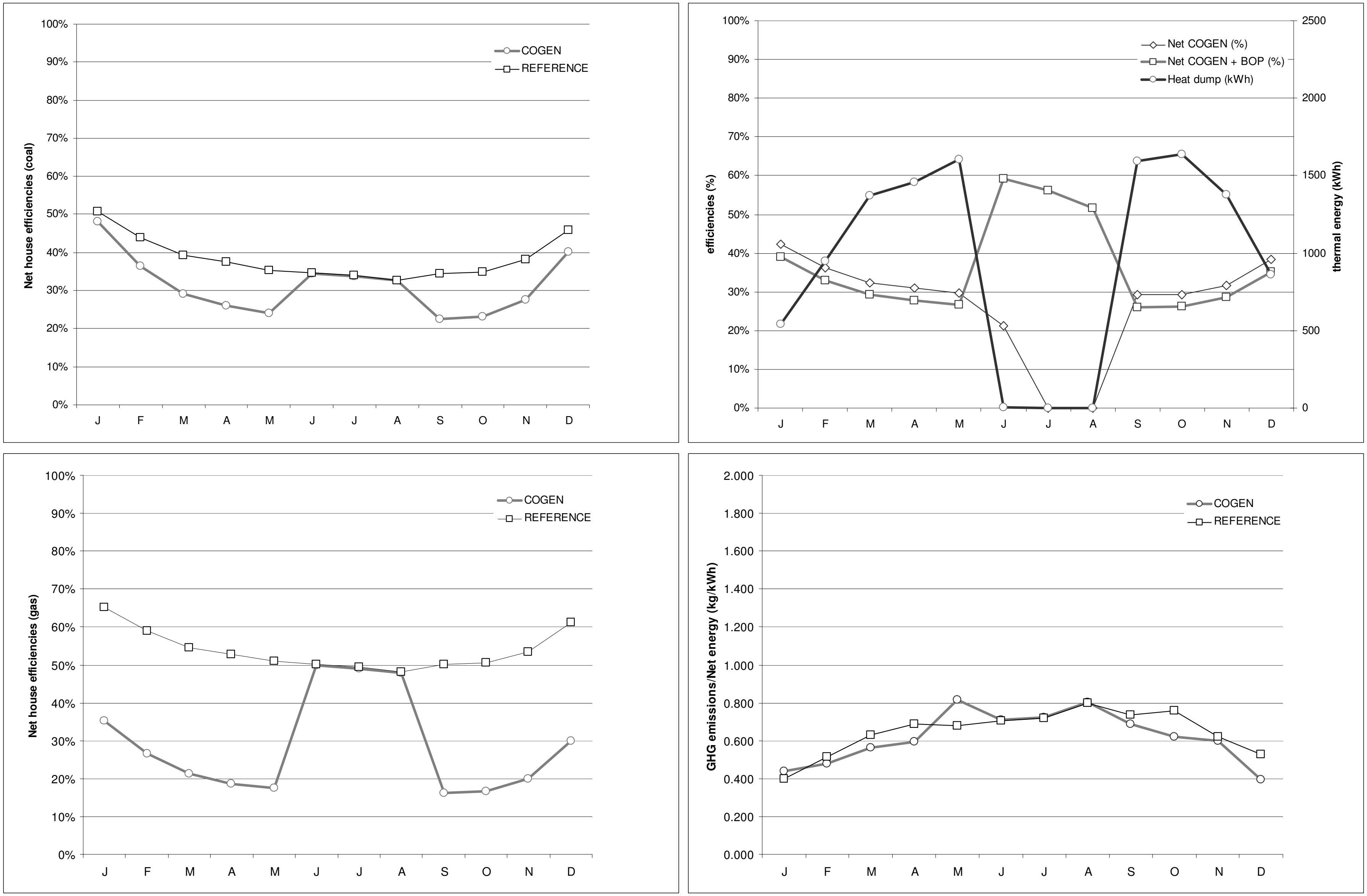
CASE ***SOFC 510***

House	Average size, superior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

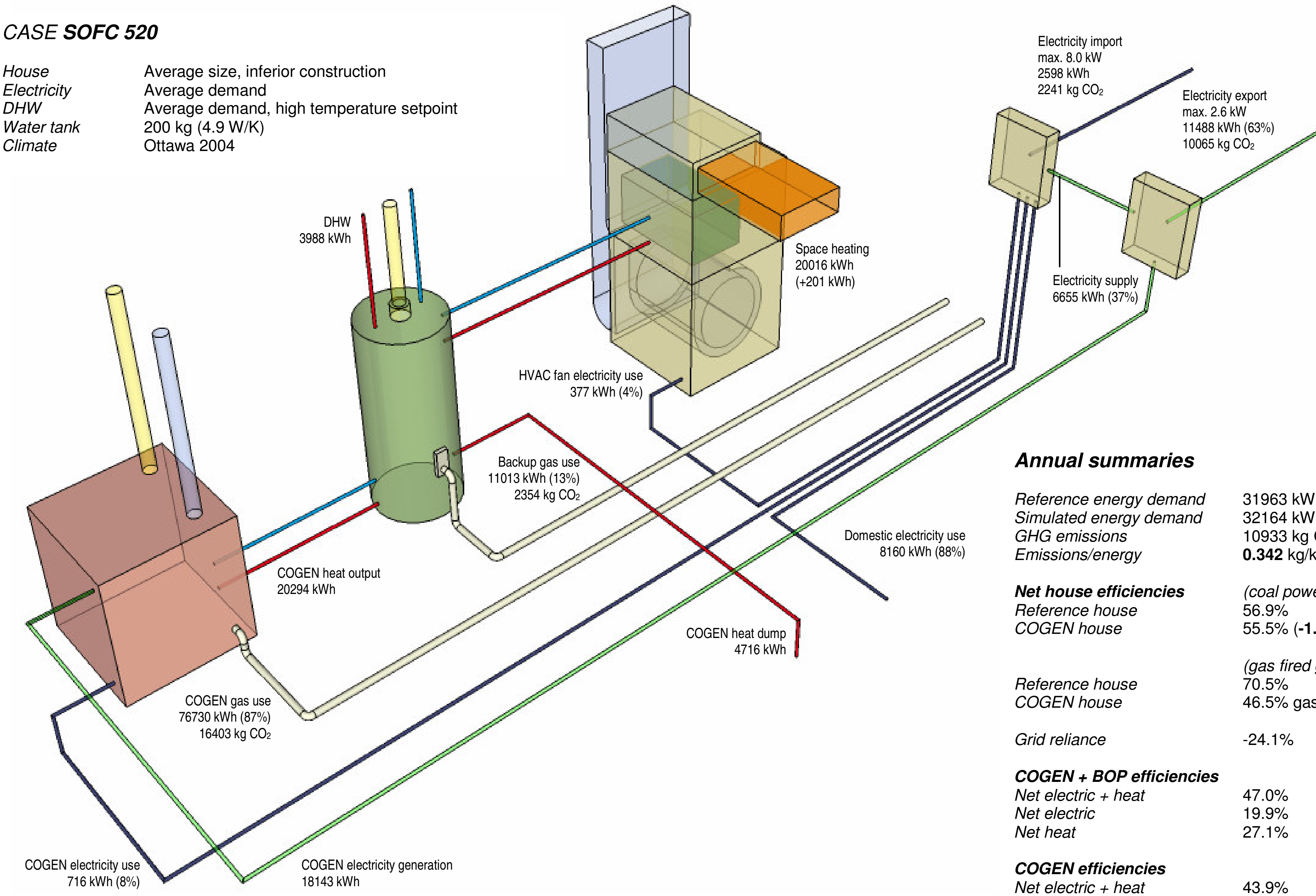
Reference energy demand	14425 kWh
Simulated energy demand	14534 kWh (**+0.8%**)
GHG emissions	8413 kg CO_2 (**-5.0%**)
Emissions/energy	**0.583** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	39.3%
COGEN house	31.4% (**-8.0%-p.**)
	(gas fired grid)
Reference house	54.9%
COGEN house	24.9% gas (**-30.0%-p.**)
Grid reliance	-114.7%
COGEN + BOP efficiencies	
Net electric + heat	30.6%
Net electric	22.6%
Net heat	8.0%
COGEN efficiencies	
Net electric + heat	33.4%
Net electric	23.6%
Gross heat	24.6%
Net heat	9.7%
COGEN heat dump/output	60.4%



CASE SOFC 510 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

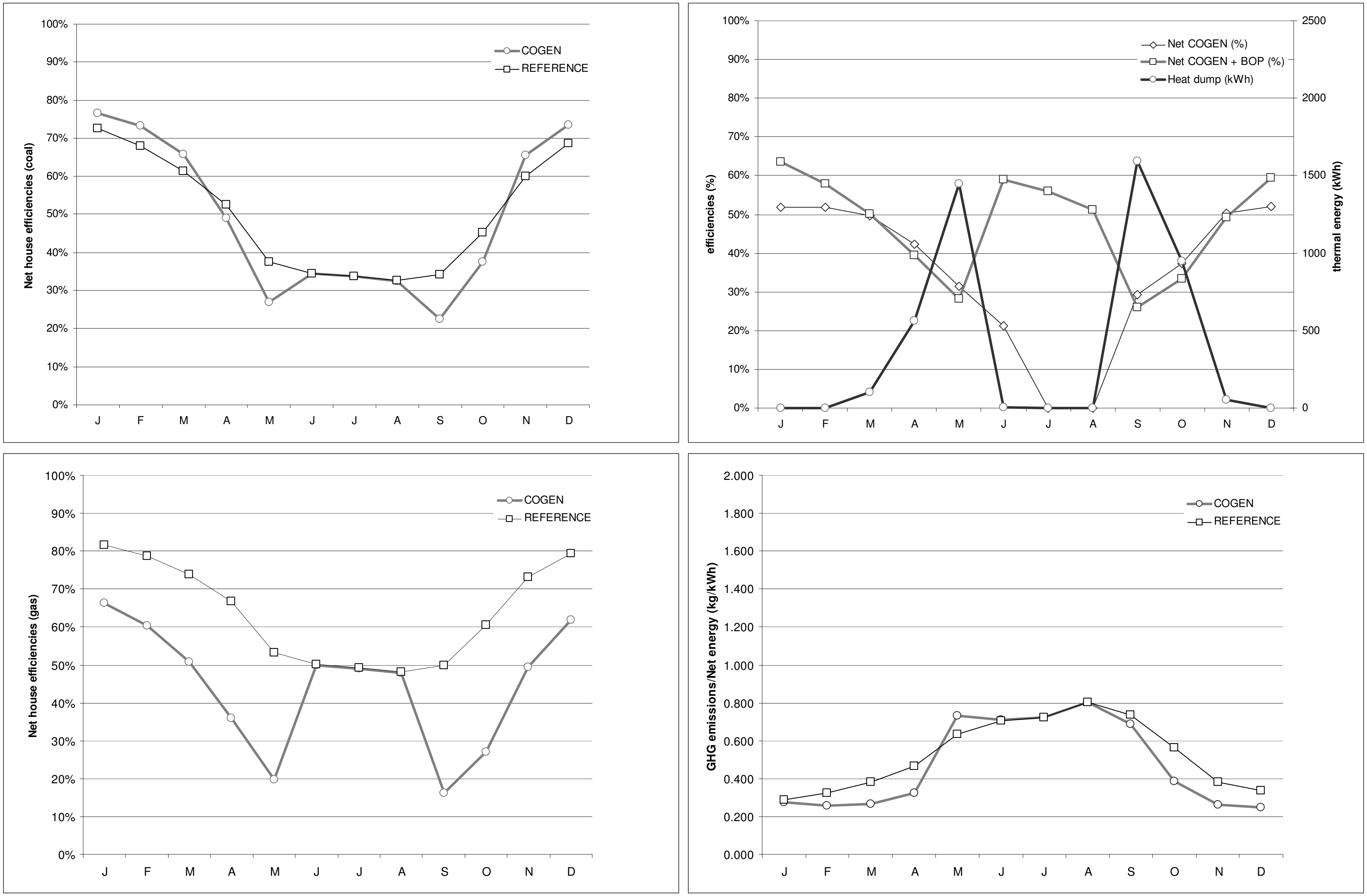
CASE ***SOFC 520***

House	Average size, inferior construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	31963 kWh
Simulated energy demand	32164 kWh (**+0.6%**)
GHG emissions	10933 kg CO_2 (**-16.3%**)
Emissions/energy	**0.342** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	56.9%
COGEN house	55.5% (**-1.4%-p.**)
	(gas fired grid)
Reference house	70.5%
COGEN house	46.5% gas (**-24.0%-p.**)
Grid reliance	-24.1%
COGEN + BOP efficiencies	
Net electric + heat	47.0%
Net electric	19.9%
Net heat	27.1%
COGEN efficiencies	
Net electric + heat	43.9%
Net electric	23.6%
Gross heat	26.4%
Net heat	20.3%
COGEN heat dump/output	23.2%

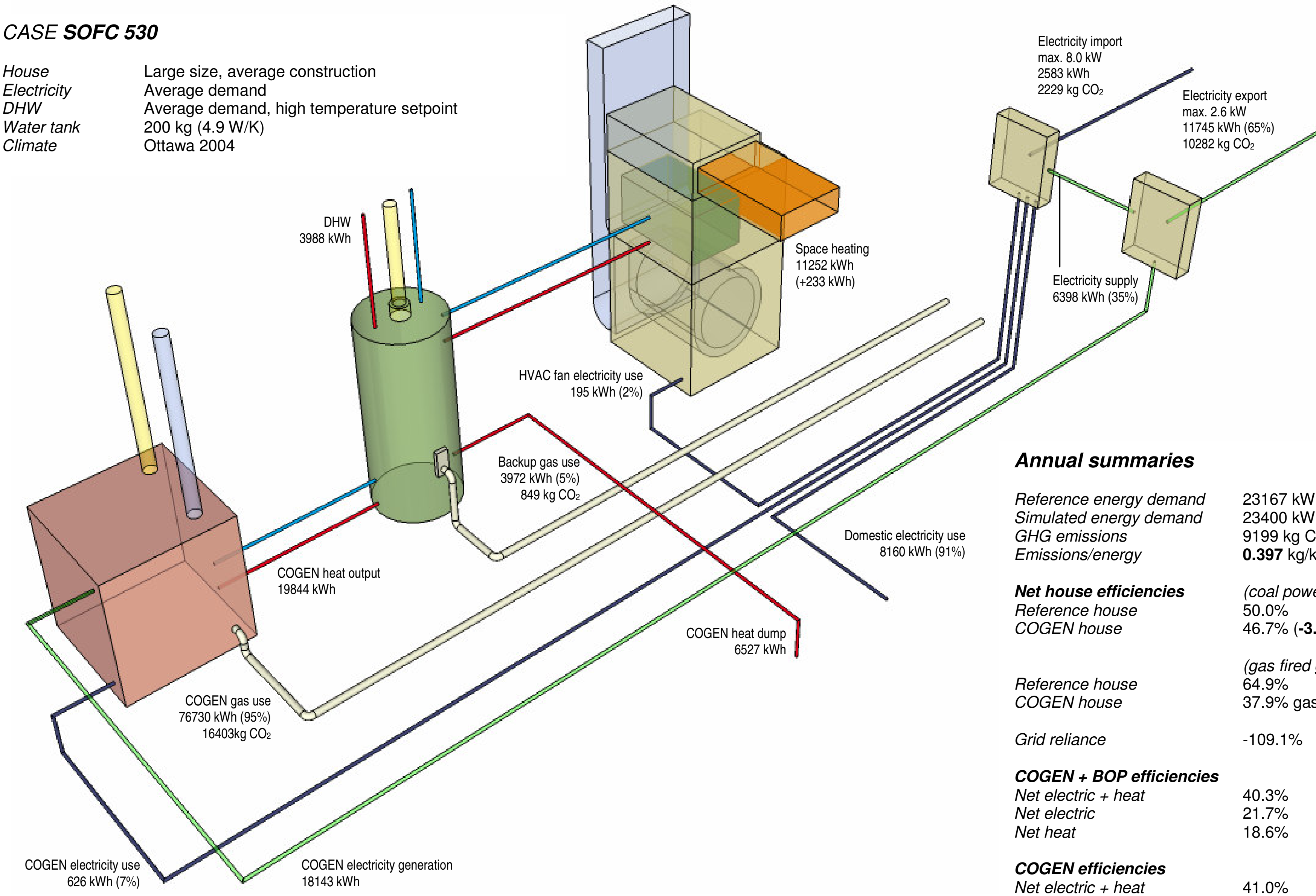


CASE SOFC 520

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

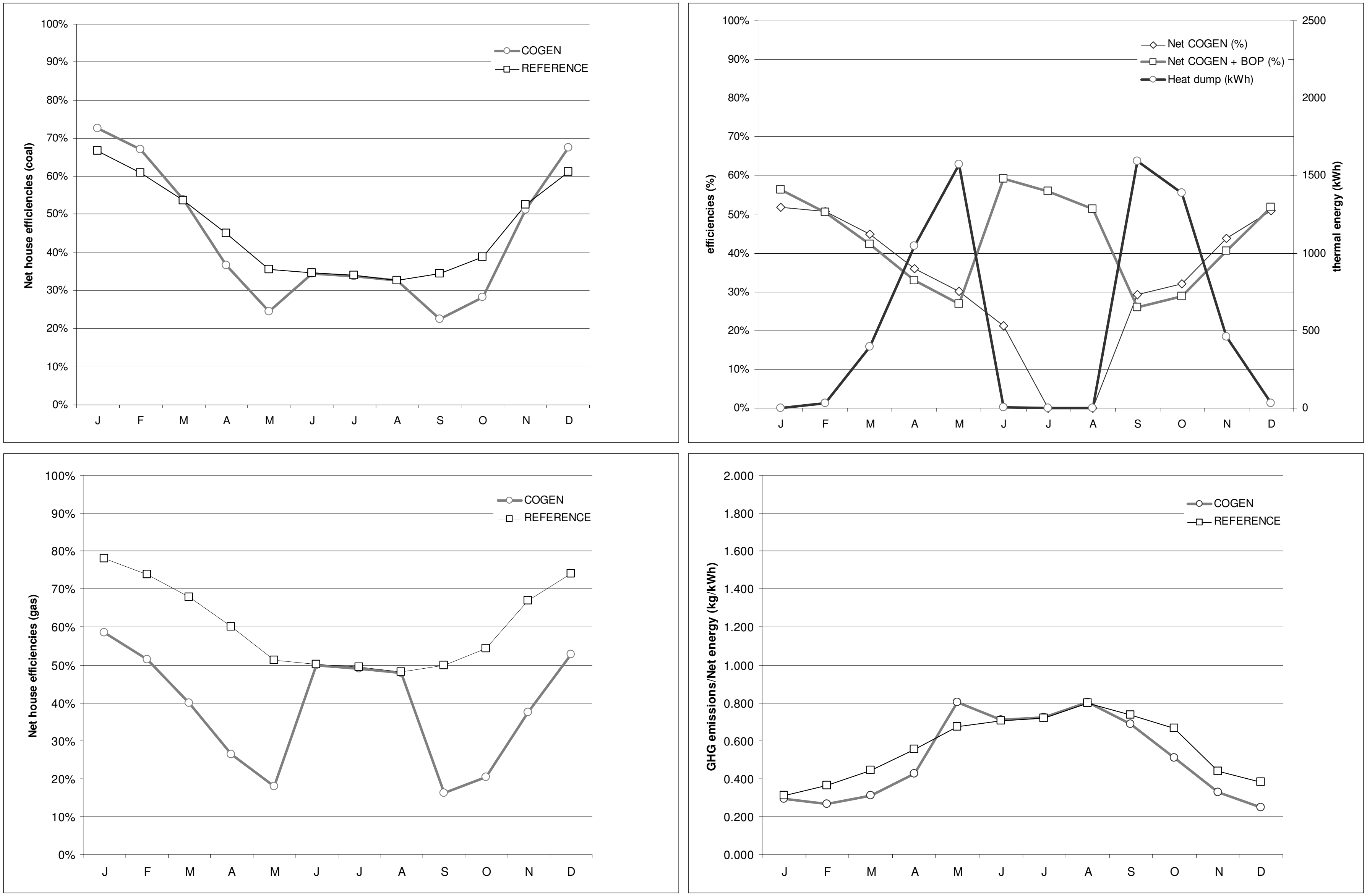
CASE ***SOFC 530***

House	Large size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

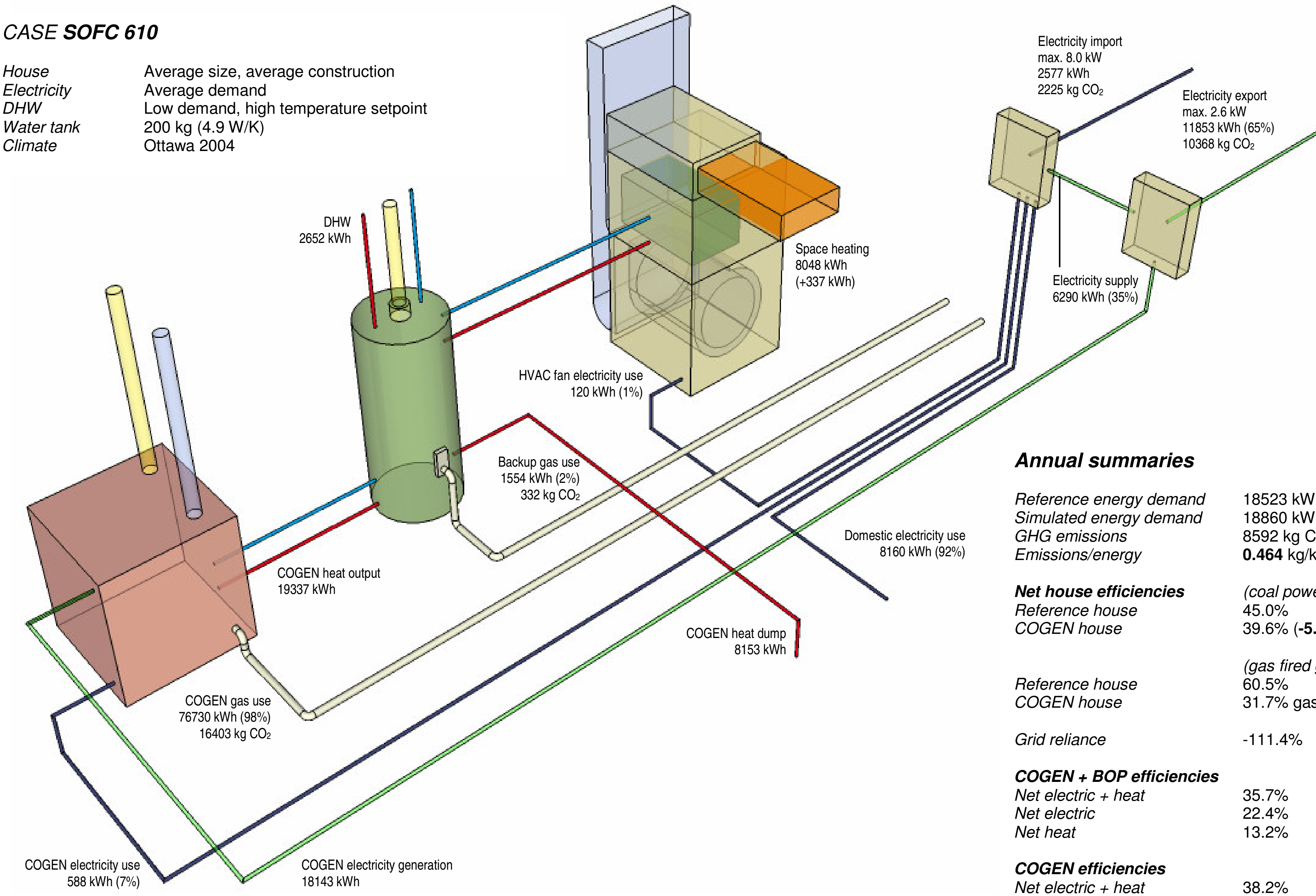
Reference energy demand	23167 kWh
Simulated energy demand	23400 kWh (**+1.0%**)
GHG emissions	9199 kg CO_2 (**-15.8%**)
Emissions/energy	**0.397** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	50.0%
COGEN house	46.7% (**-3.3%-p.**)
	(gas fired grid)
Reference house	64.9%
COGEN house	37.9% gas (**-27.0%-p.**)
Grid reliance	-109.1%
COGEN + BOP efficiencies	
Net electric + heat	40.3%
Net electric	21.7%
Net heat	18.6%
COGEN efficiencies	
Net electric + heat	41.0%
Net electric	23.6%
Gross heat	25.9%
Net heat	17.4%
COGEN heat dump/output	32.9%



CASE SOFC 530 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

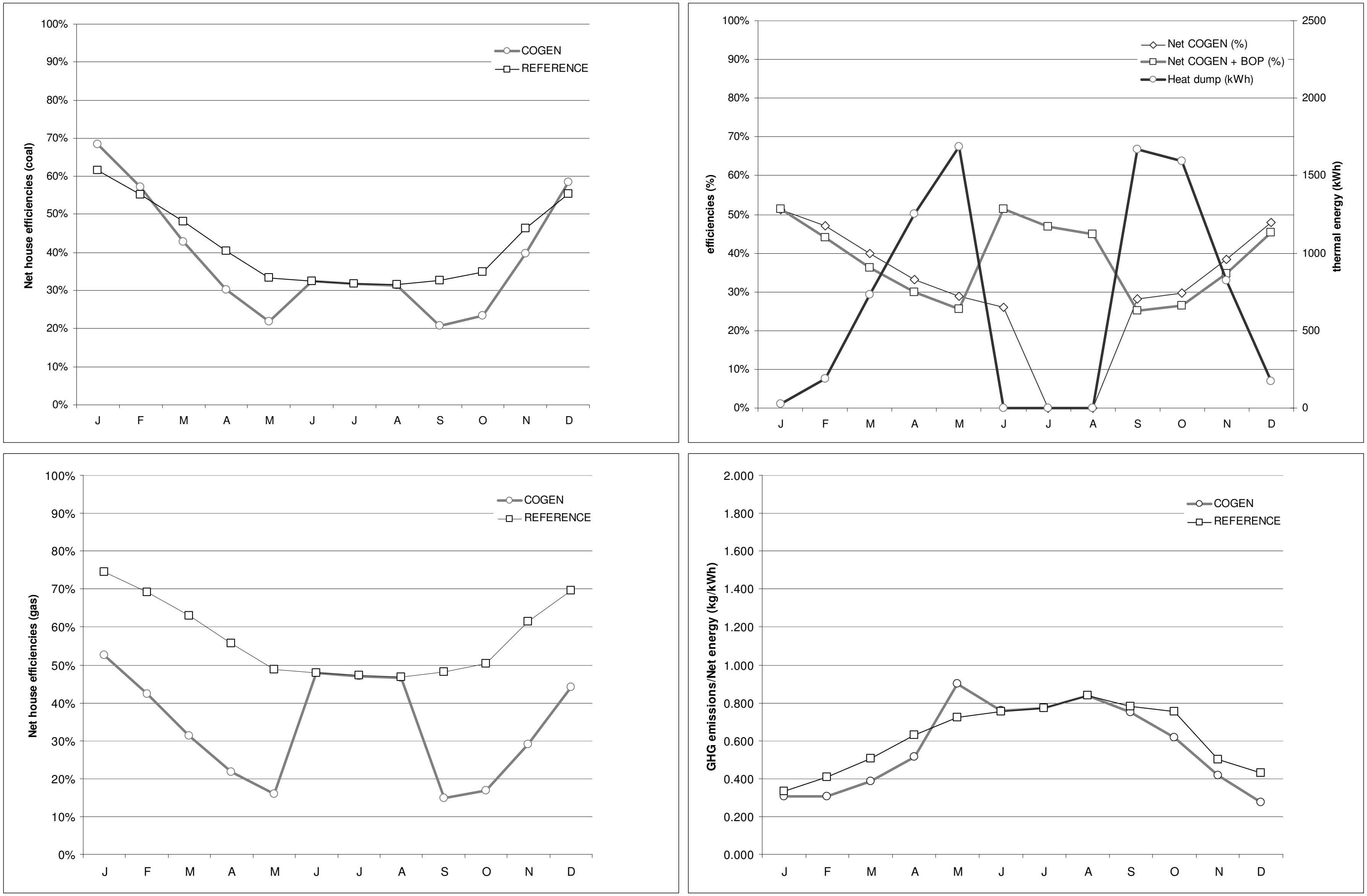
CASE ***SOFC 610***

House	Average size, average construction
Electricity	Average demand
DHW	Low demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	18523 kWh
Simulated energy demand	18860 kWh (**+1.8%**)
GHG emissions	8592 kg CO_2 (**-12.5%**)
Emissions/energy	**0.464** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	45.0%
COGEN house	39.6% (**-5.4%-p.**)
	(gas fired grid)
Reference house	60.5%
COGEN house	31.7% gas (**-28.8%-p.**)
Grid reliance	-111.4%
COGEN + BOP efficiencies	
Net electric + heat	35.7%
Net electric	22.4%
Net heat	13.2%
COGEN efficiencies	
Net electric + heat	38.2%
Net electric	23.6%
Gross heat	25.2%
Net heat	14.6%
COGEN heat dump/output	42.2%

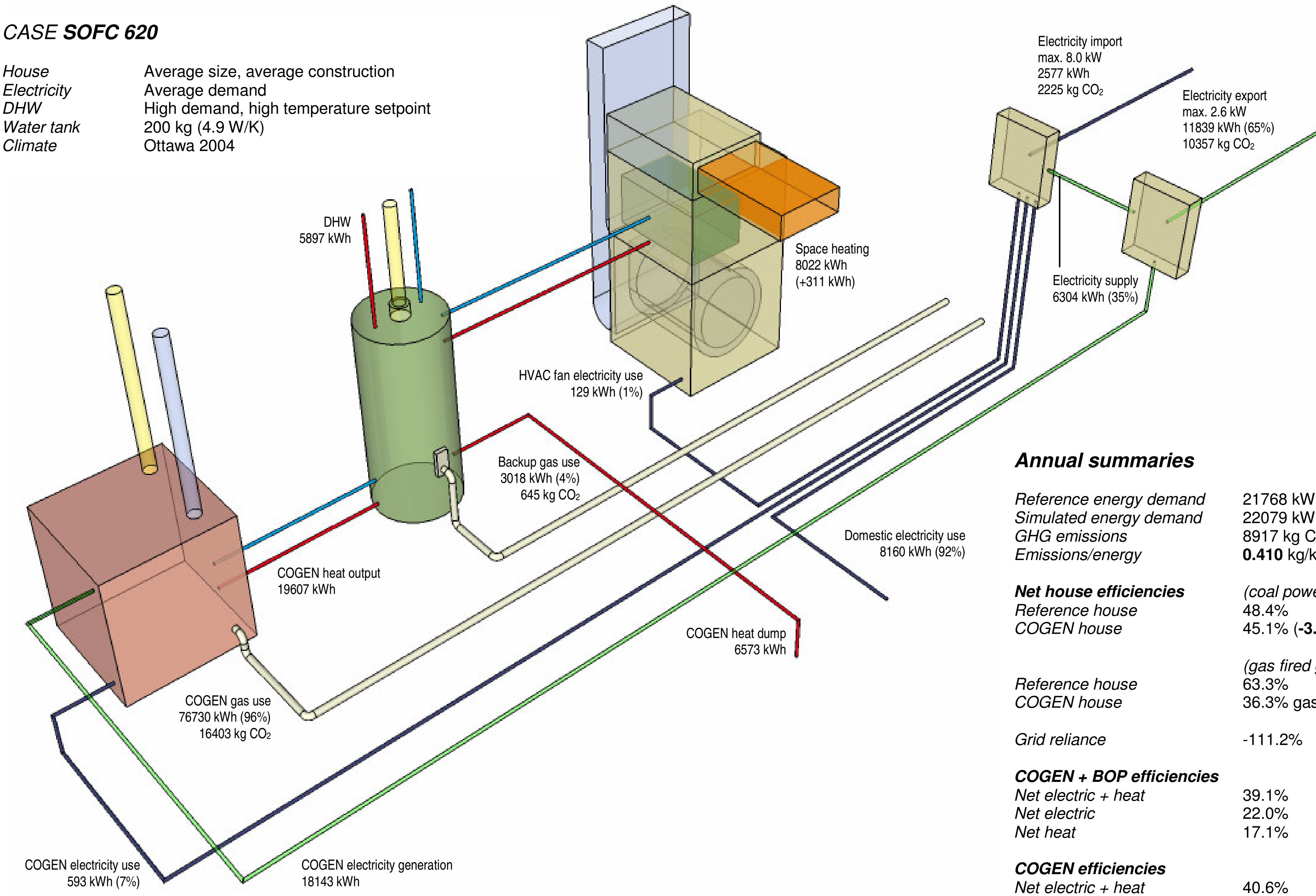


CASE SOFC 610

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

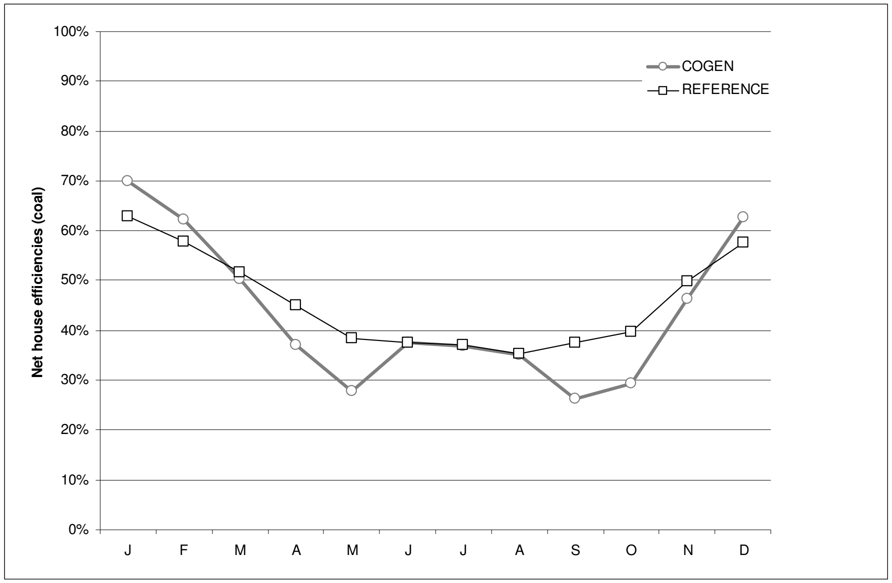
CASE ***SOFC 620***

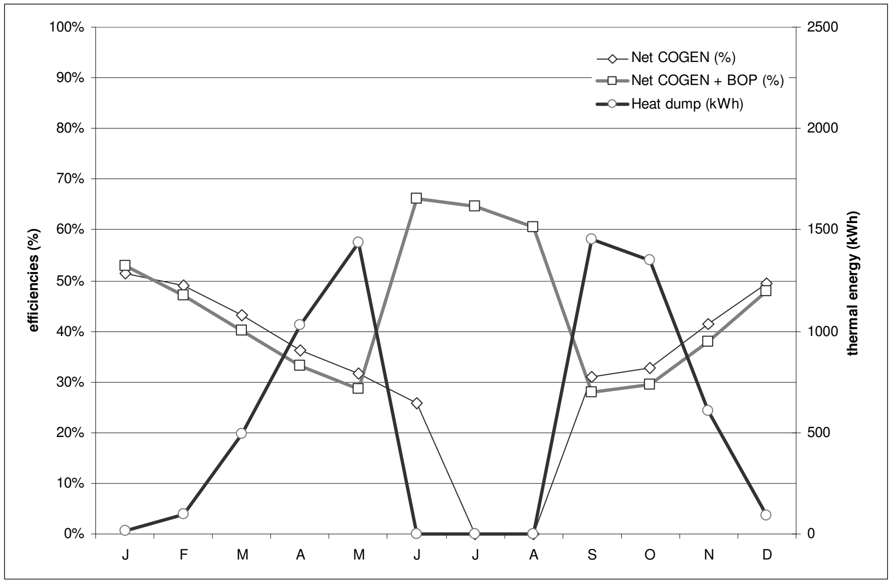
House	Average size, average construction
Electricity	Average demand
DHW	High demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004

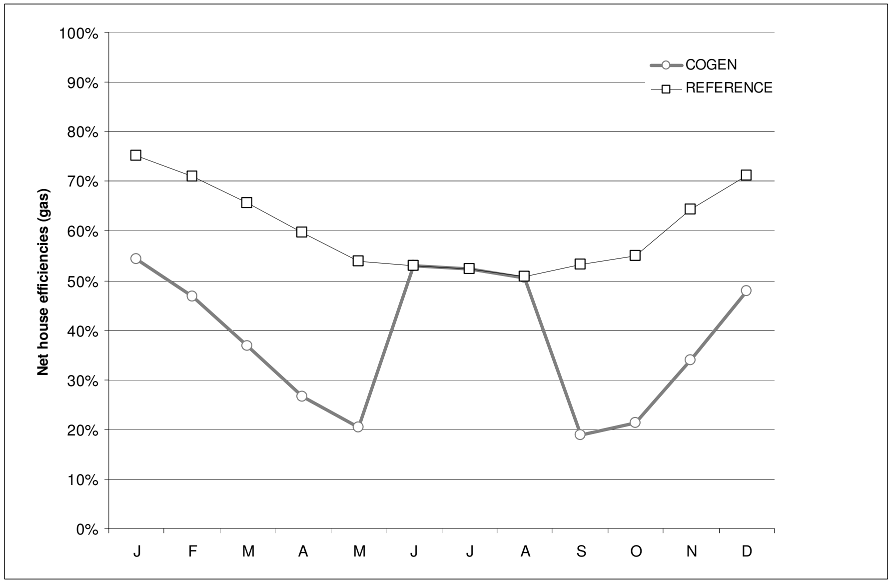


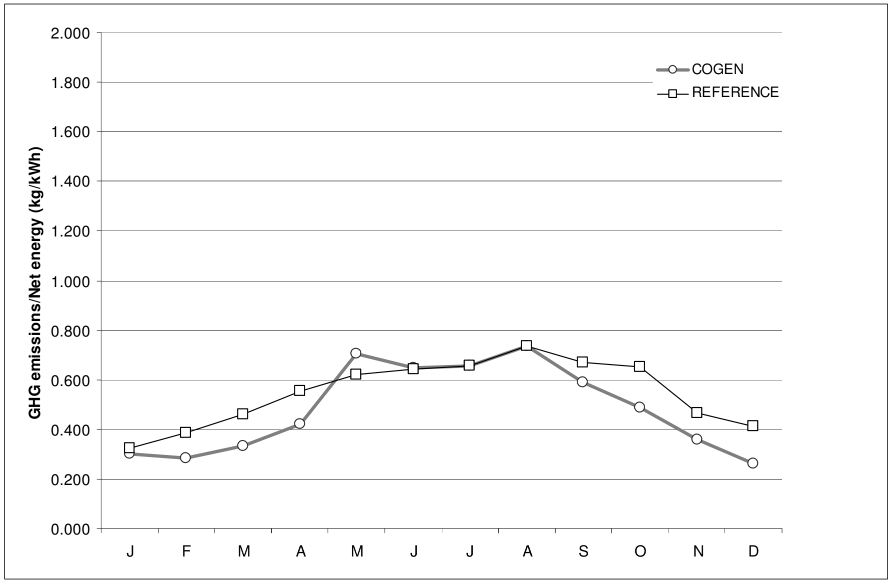
Annual summaries

Reference energy demand	21768 kWh
Simulated energy demand	22079 kWh (**+1.4%**)
GHG emissions	8917 kg CO_2 (**-16.1%**)
Emissions/energy	**0.410** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	48.4%
COGEN house	45.1% (**-3.4%-p.**)
	(gas fired grid)
Reference house	63.3%
COGEN house	36.3% gas (**-27.0%-p.**)
Grid reliance	-111.2%
COGEN + BOP efficiencies	
Net electric + heat	39.1%
Net electric	22.0%
Net heat	17.1%
COGEN efficiencies	
Net electric + heat	40.6%
Net electric	23.6%
Gross heat	25.6%
Net heat	17.0%
COGEN heat dump/output	33.5%







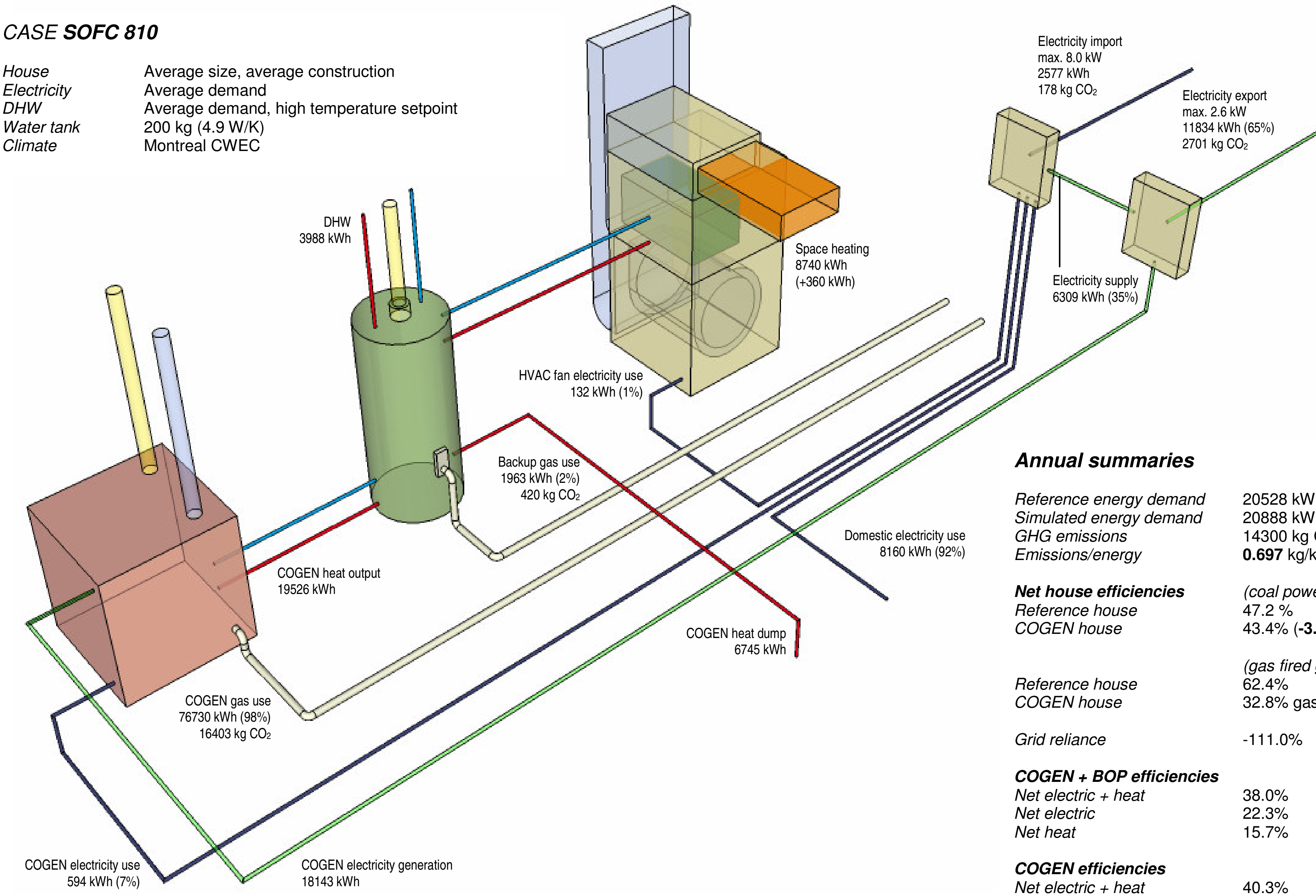


CASE SOFC 620

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

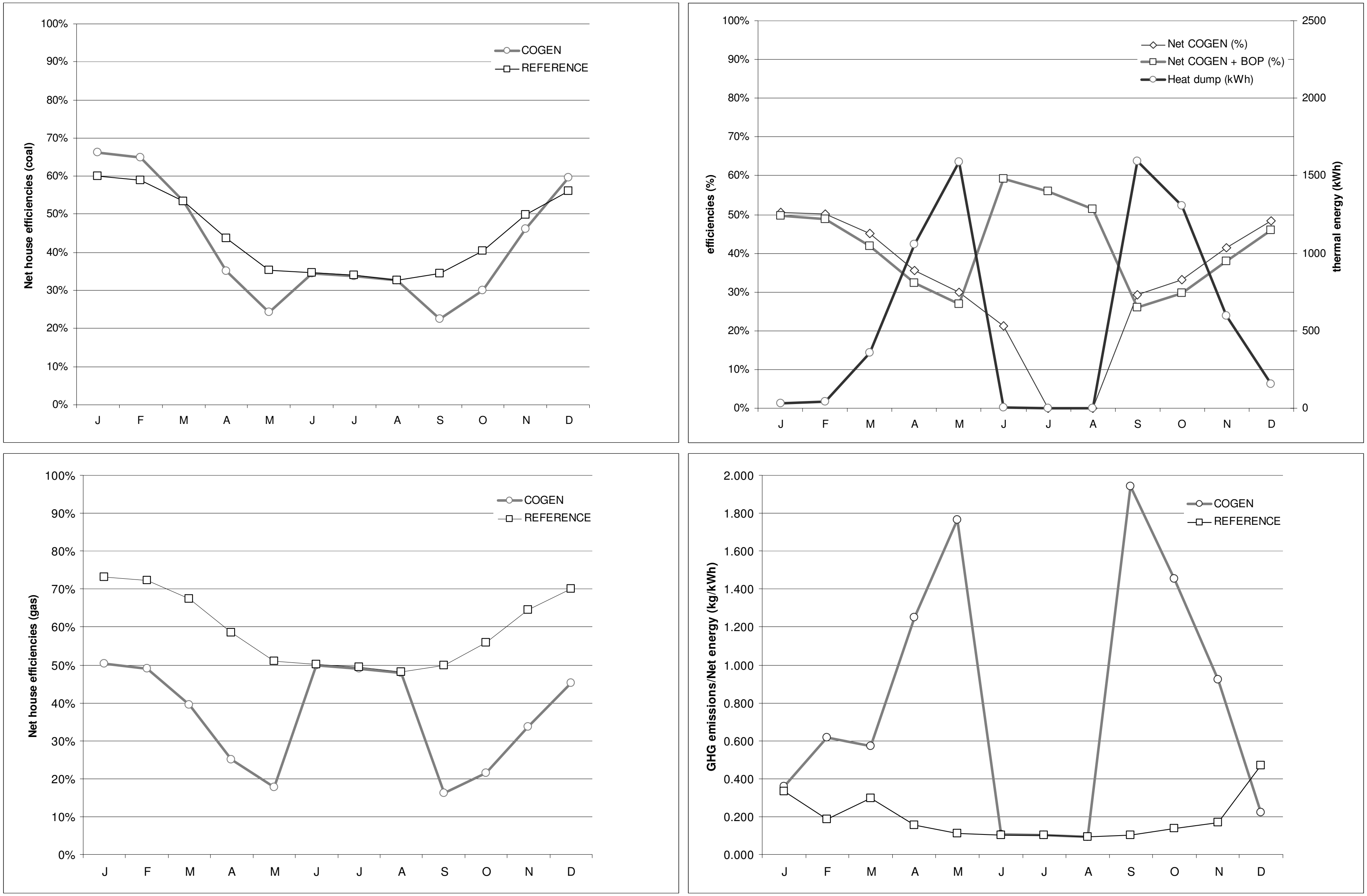
CASE **SOFC 810**

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Montreal CWEC



Annual summaries

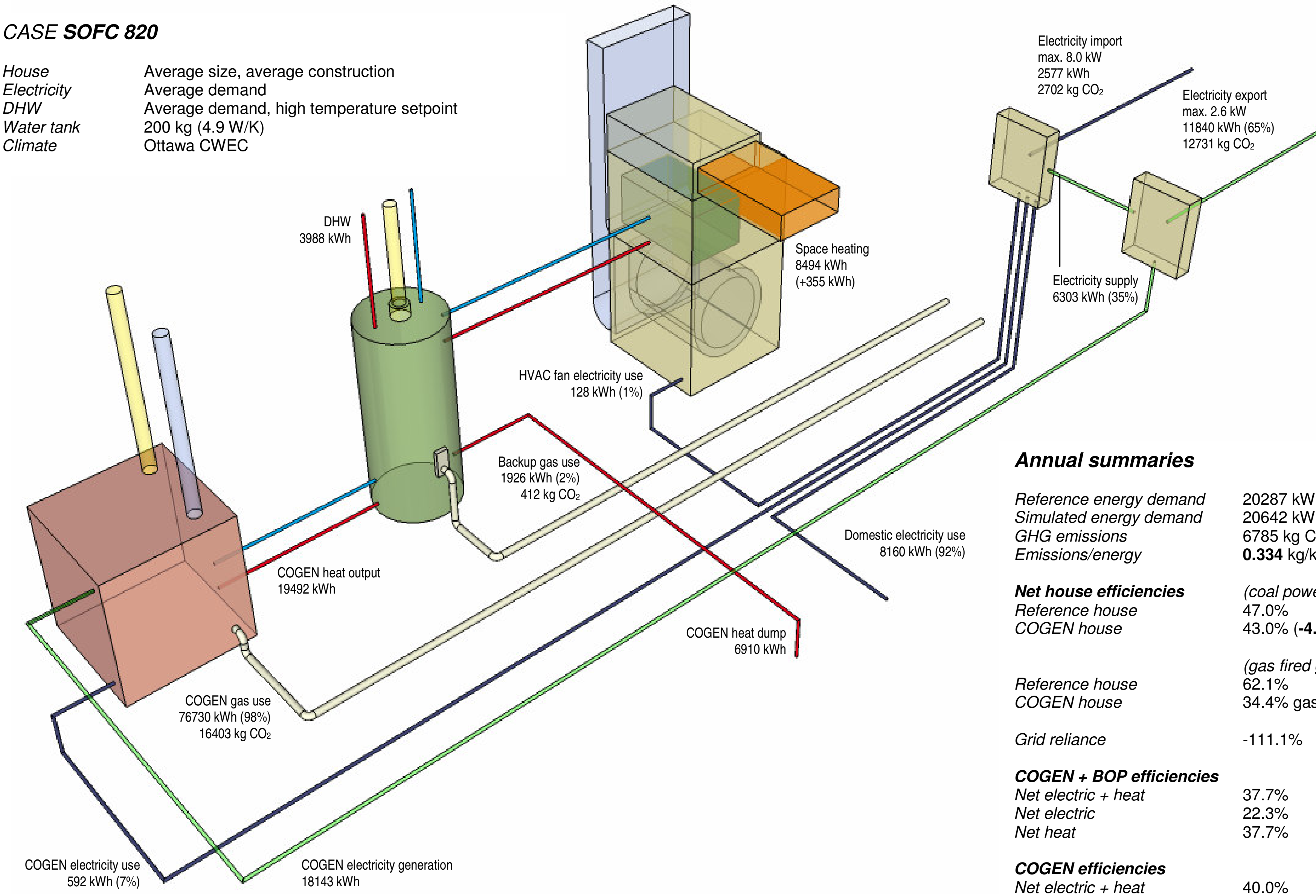
Reference energy demand	20528 kWh
Simulated energy demand	20888 kWh (**+1.8%**)
GHG emissions	14300 kg CO_2 (**+196%**)
Emissions/energy	**0.697** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.2 %
COGEN house	43.4% (**-3.8%-p.**)
	(gas fired grid)
Reference house	62.4%
COGEN house	32.8% gas (**-27.6%-p.**)
Grid reliance	-111.0%
COGEN + BOP efficiencies	
Net electric + heat	38.0%
Net electric	22.3%
Net heat	15.7%
COGEN efficiencies	
Net electric + heat	40.3%
Net electric	23.6%
Gross heat	25.4%
Net heat	16.7%
COGEN heat dump/output	34.5%



CASE SOFC 810 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

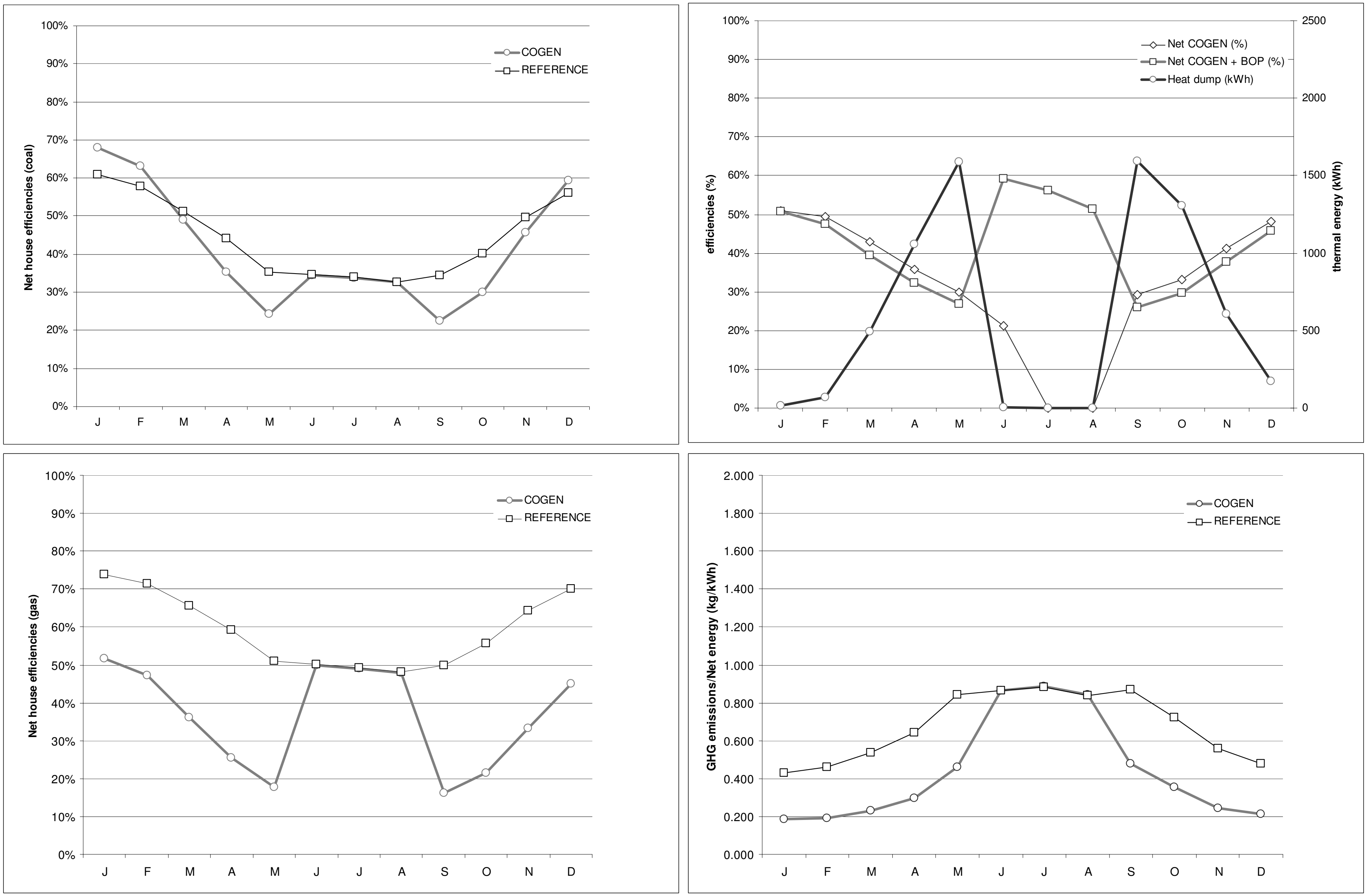
CASE ***SOFC 820***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa CWEC



Annual summaries

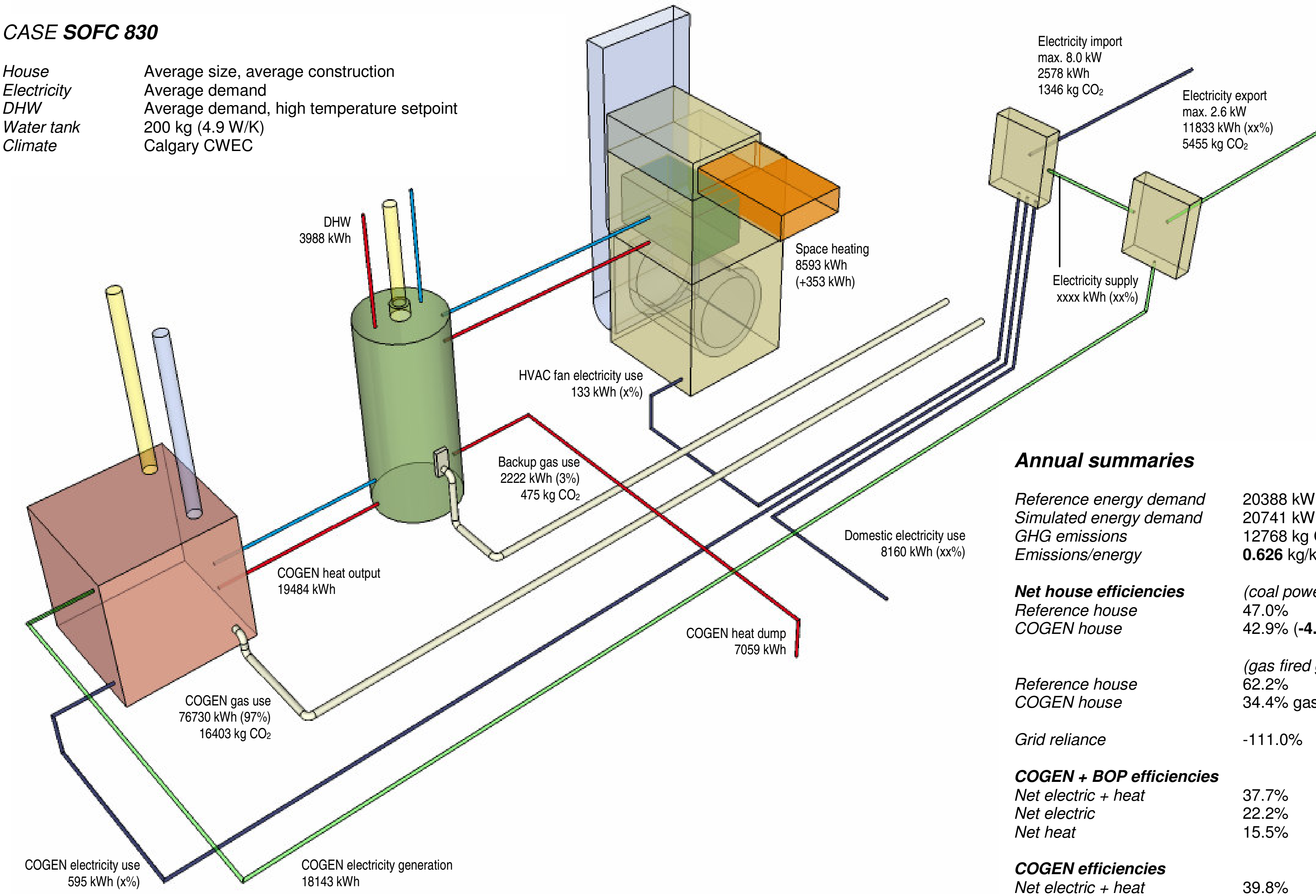
Reference energy demand	20287 kWh
Simulated energy demand	20642 kWh (**+1.8%**)
GHG emissions	6785 kg CO_2 (**-43.8%**)
Emissions/energy	**0.334** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	43.0% (**-4.0%-p.**)
	(gas fired grid)
Reference house	62.1%
COGEN house	34.4% gas (**-27.7%-p.**)
Grid reliance	-111.1%
COGEN + BOP efficiencies	
Net electric + heat	37.7%
Net electric	22.3%
Net heat	37.7%
COGEN efficiencies	
Net electric + heat	40.0%
Net electric	23.6%
Gross heat	25.4%
Net heat	16.4%
COGEN heat dump/output	35.5%



CASE SOFC 820 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

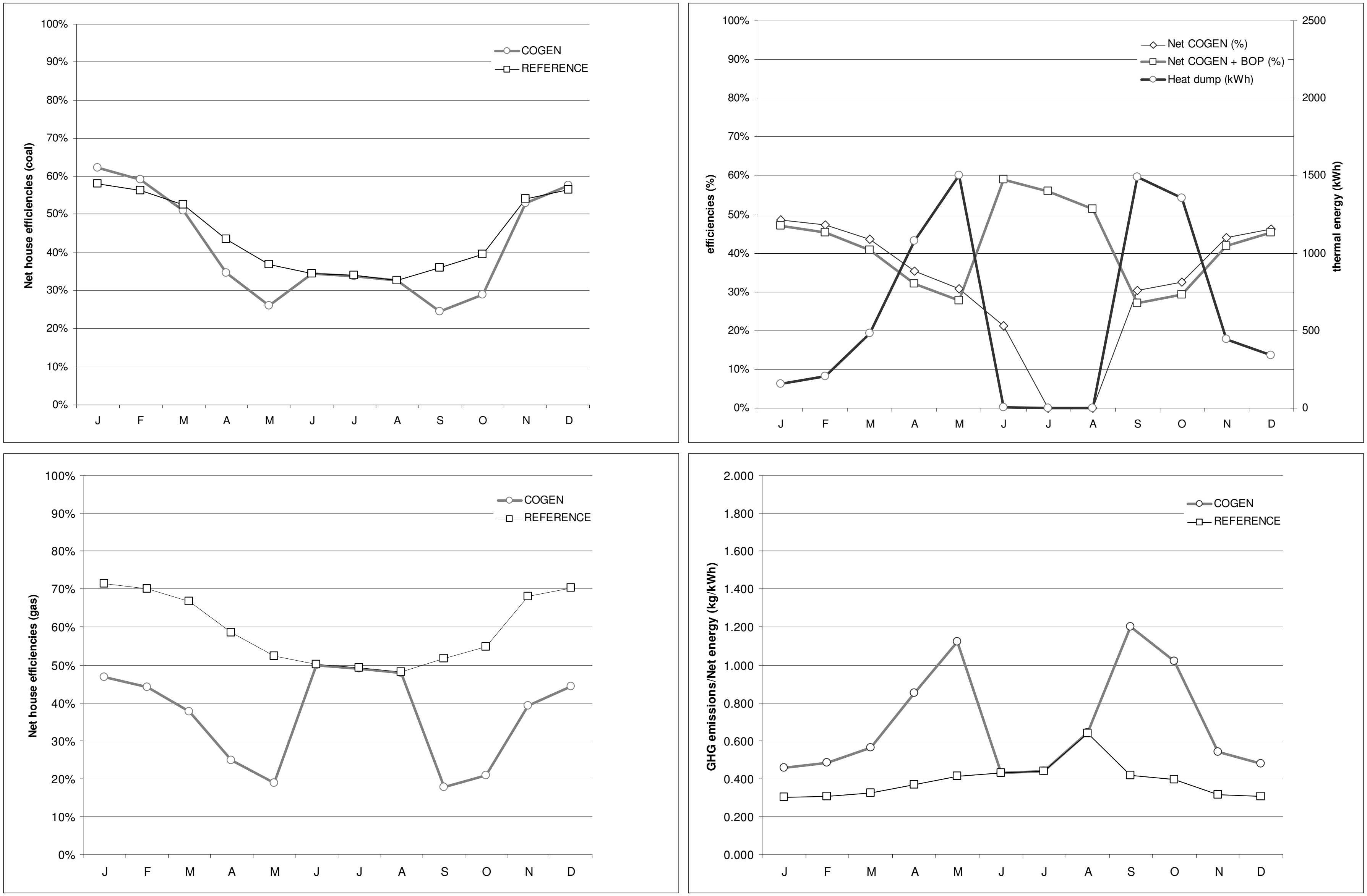
CASE ***SOFC 830***

House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Calgary CWEC



Annual summaries

Reference energy demand	20388 kWh
Simulated energy demand	20741 kWh (**+1.7%**)
GHG emissions	12768 kg CO_2 (**+77.0%**)
Emissions/energy	**0.626** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.0%
COGEN house	42.9% (**-4.1%-p.**)
	(gas fired grid)
Reference house	62.2%
COGEN house	34.4% gas (**-27.7%-p.**)
Grid reliance	-111.0%
COGEN + BOP efficiencies	
Net electric + heat	37.7%
Net electric	22.2%
Net heat	15.5%
COGEN efficiencies	
Net electric + heat	39.8%
Net electric	23.6%
Gross heat	25.4%
Net heat	16.2%
COGEN heat dump/output	36.2%

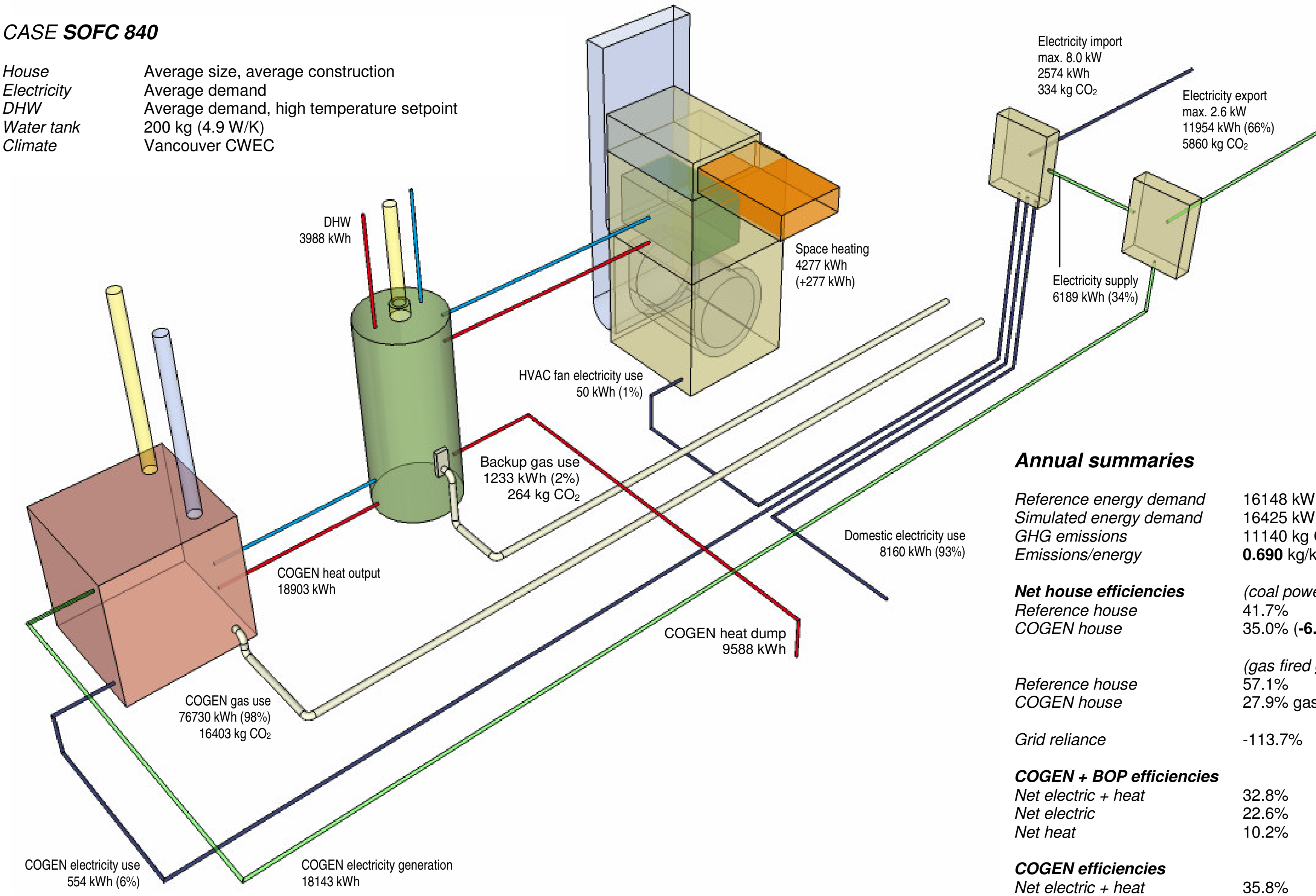


CASE SOFC 830

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

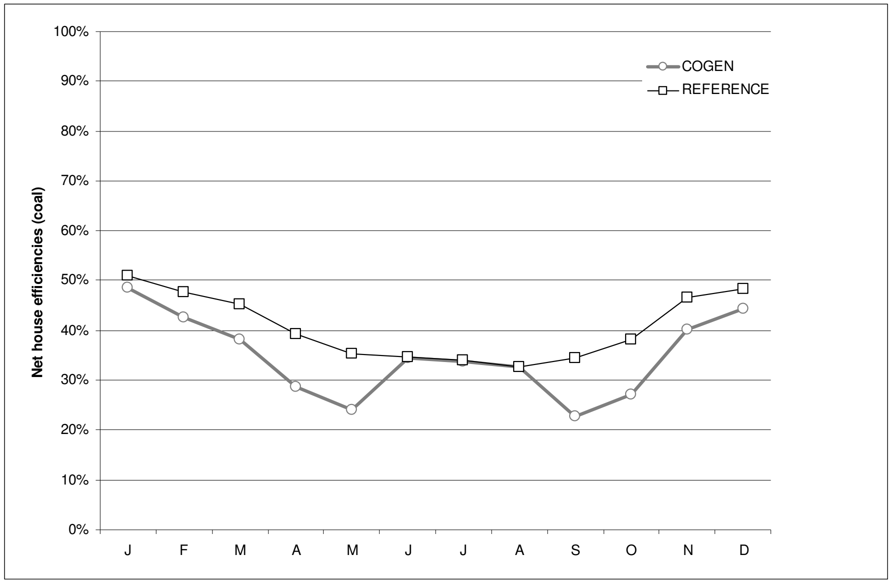
CASE **SOFC 840**

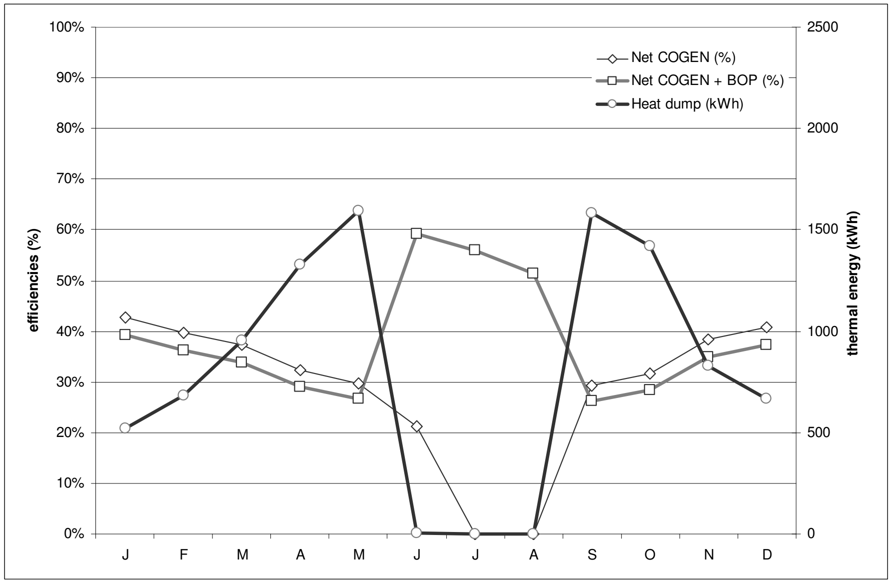
House	Average size, average construction
Electricity	Average demand
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Vancouver CWEC

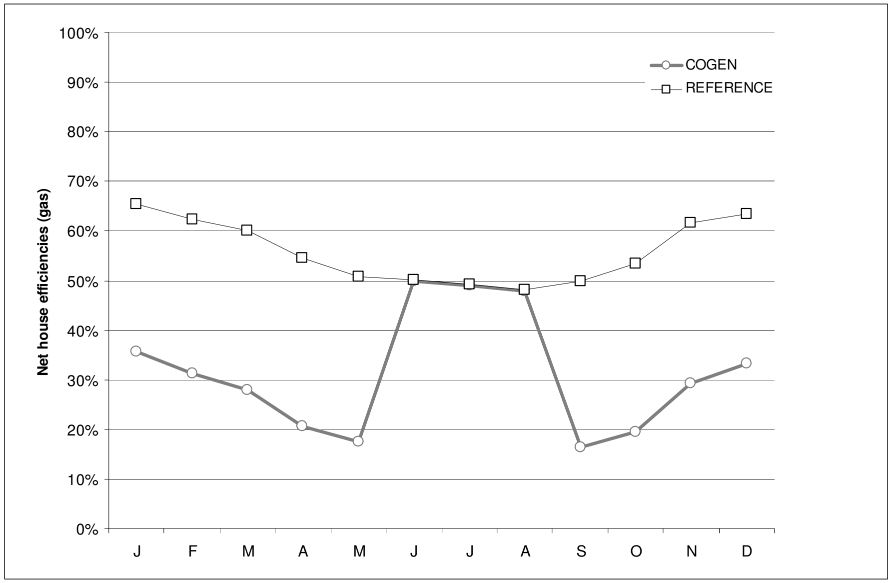


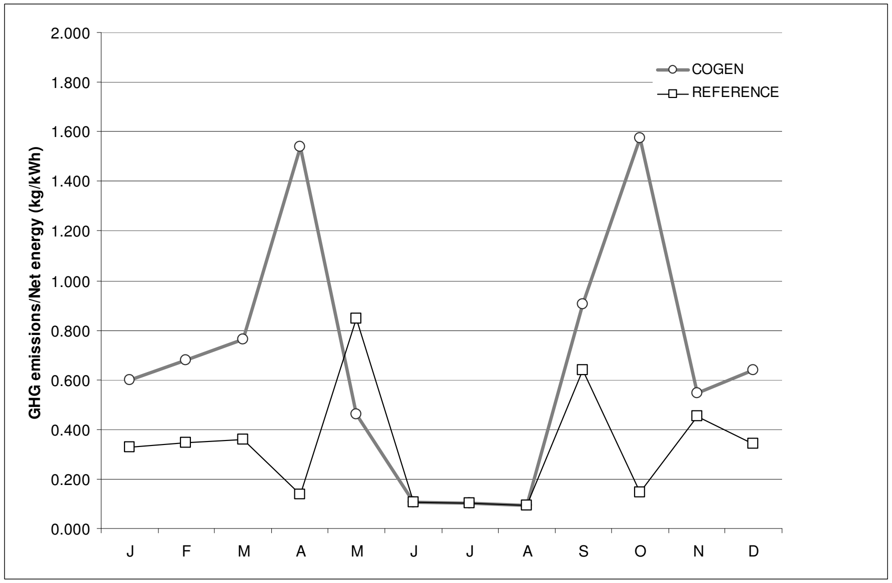
Annual summaries

Reference energy demand	16148 kWh
Simulated energy demand	16425 kWh (**+1.7%**)
GHG emissions	11140 kg CO_2 (**+105%**)
Emissions/energy	**0.690** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	41.7%
COGEN house	35.0% (**-6.7%-p.**)
	(gas fired grid)
Reference house	57.1%
COGEN house	27.9% gas (**-29.2%-p.**)
Grid reliance	-113.7%
COGEN + BOP efficiencies	
Net electric + heat	32.8%
Net electric	22.6%
Net heat	10.2%
COGEN efficiencies	
Net electric + heat	35.8%
Net electric	23.6%
Gross heat	24.6%
Net heat	12.1%
COGEN heat dump/output	50.7%







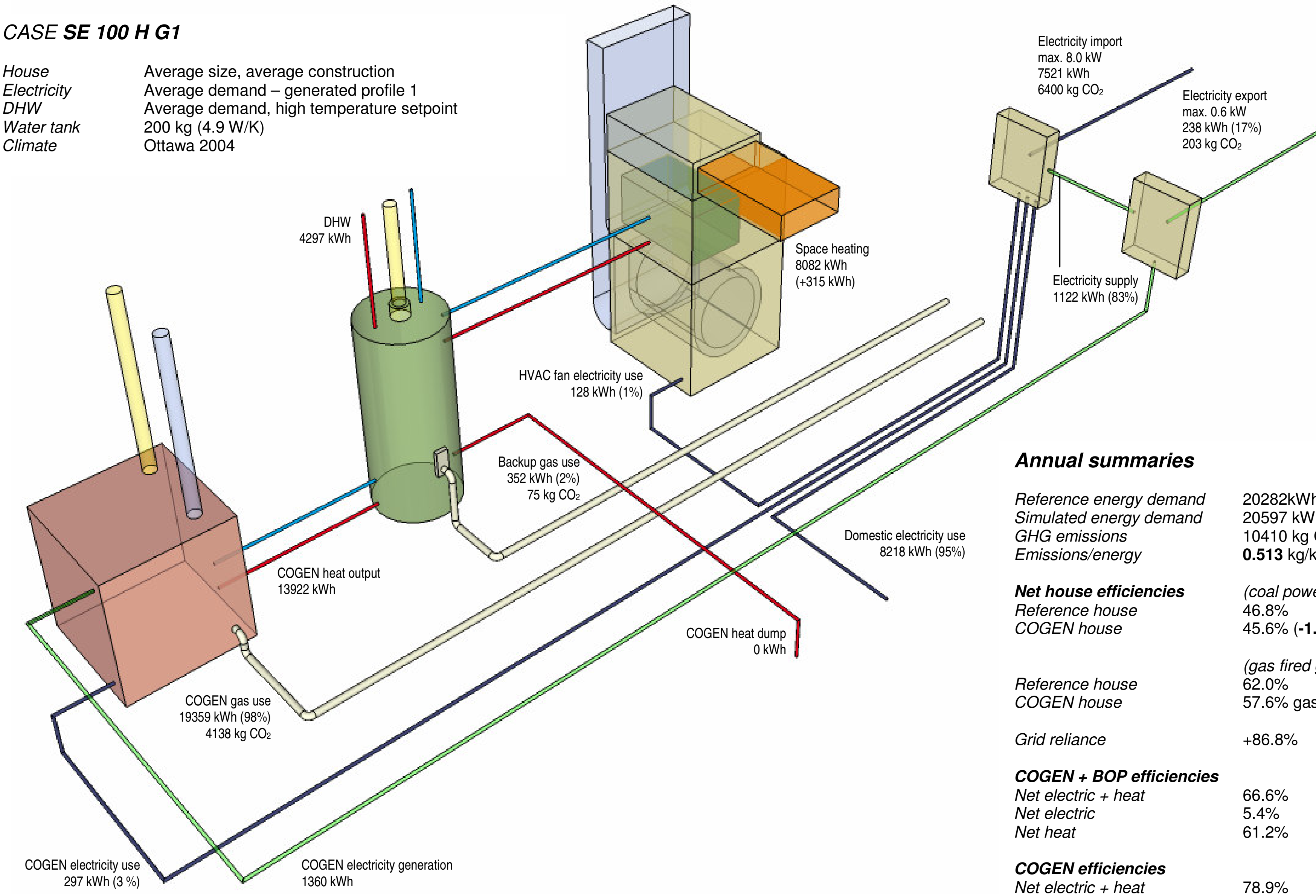


CASE SOFC 840

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.

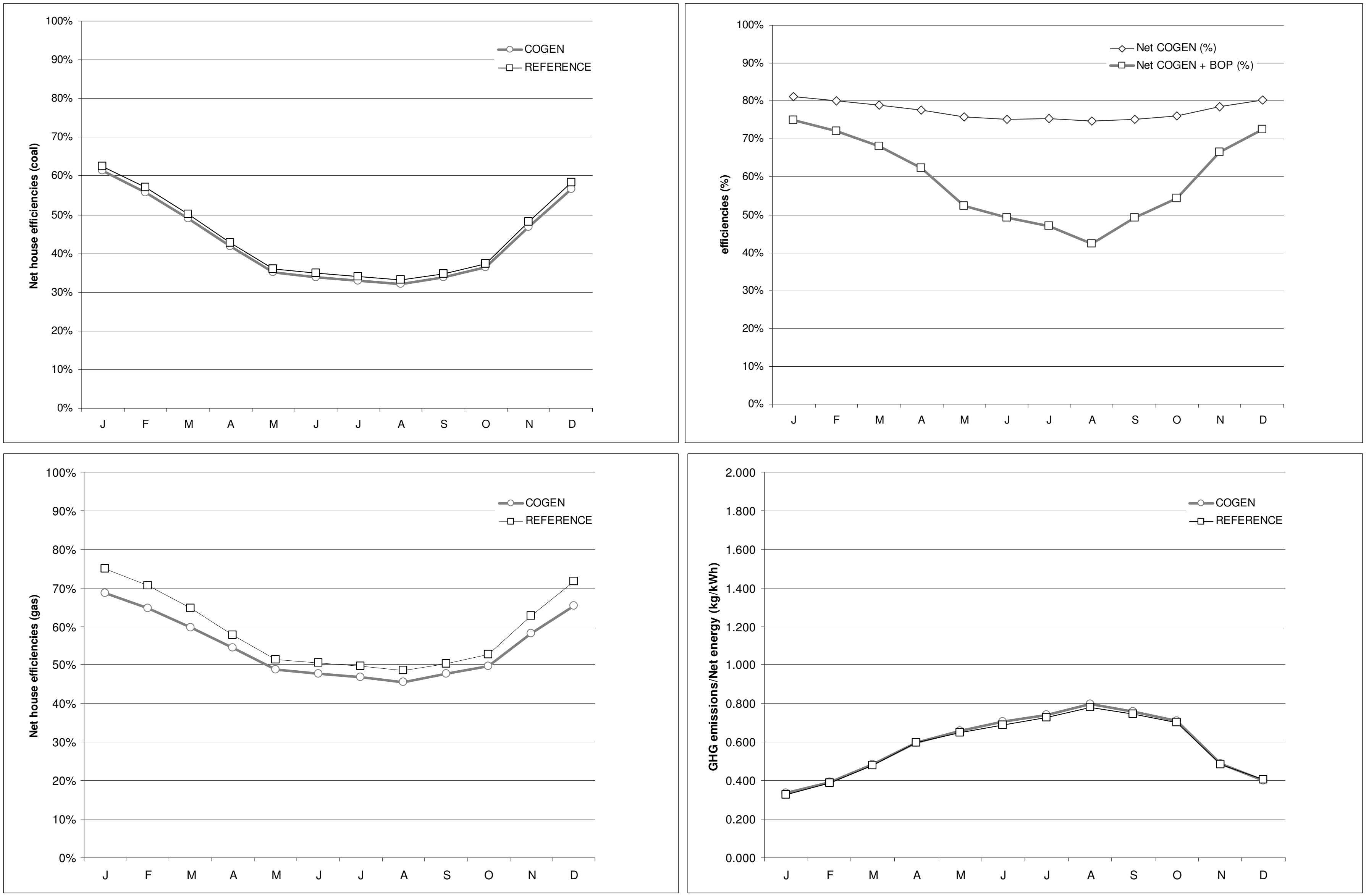
CASE ***SE 100 H G1***

House	Average size, average construction
Electricity	Average demand – generated profile 1
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

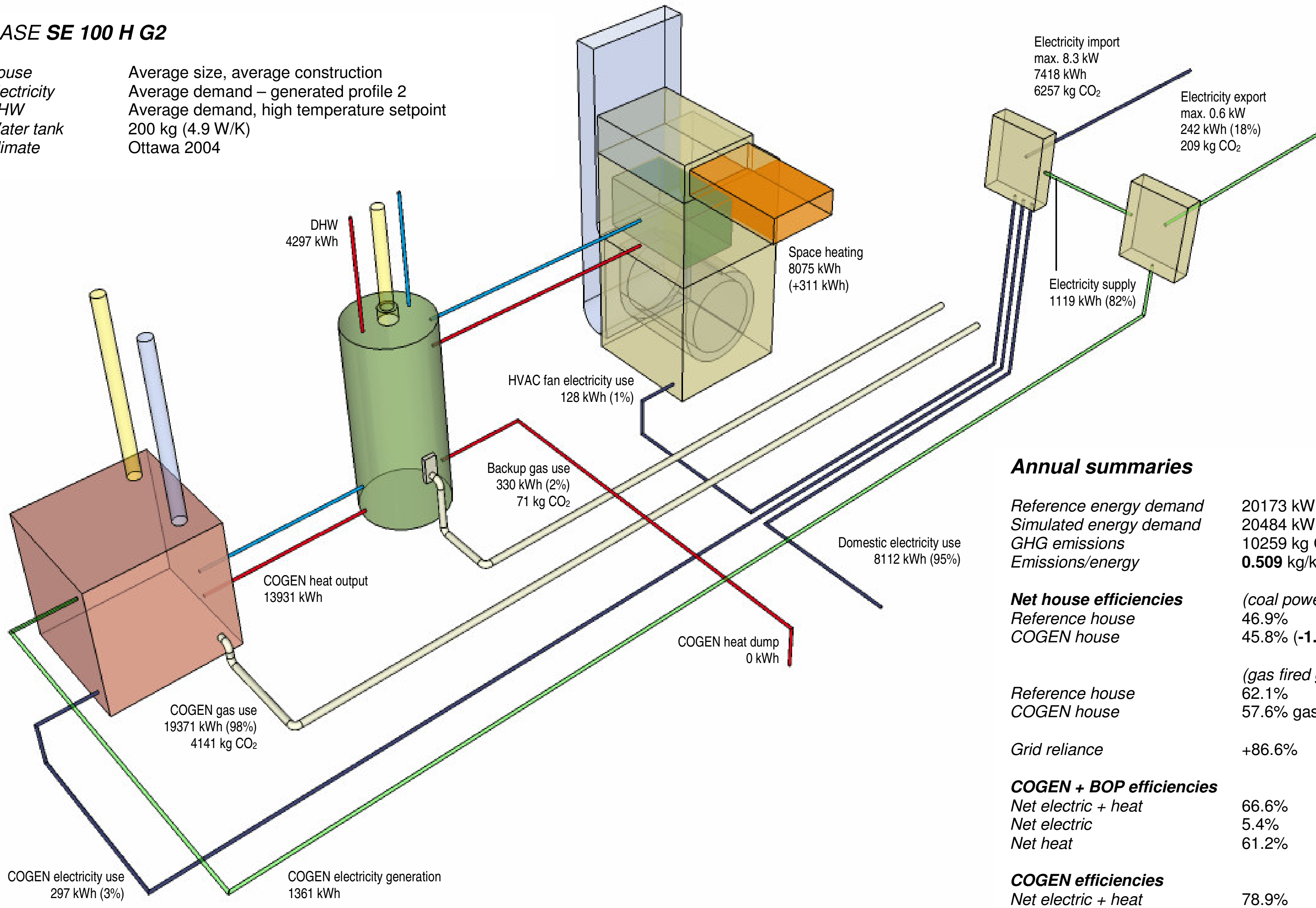
Reference energy demand	20282kWh
Simulated energy demand	20597 kWh (**+1.6%**)
GHG emissions	10410 kg CO_2 (**+1.3%**)
Emissions/energy	**0.513** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.8%
COGEN house	45.6% (**-1.2%-p.**)
	(gas fired grid)
Reference house	62.0%
COGEN house	57.6% gas (**-4.4%-p.**)
Grid reliance	+86.8%
COGEN + BOP efficiencies	
Net electric + heat	66.6%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H G1 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

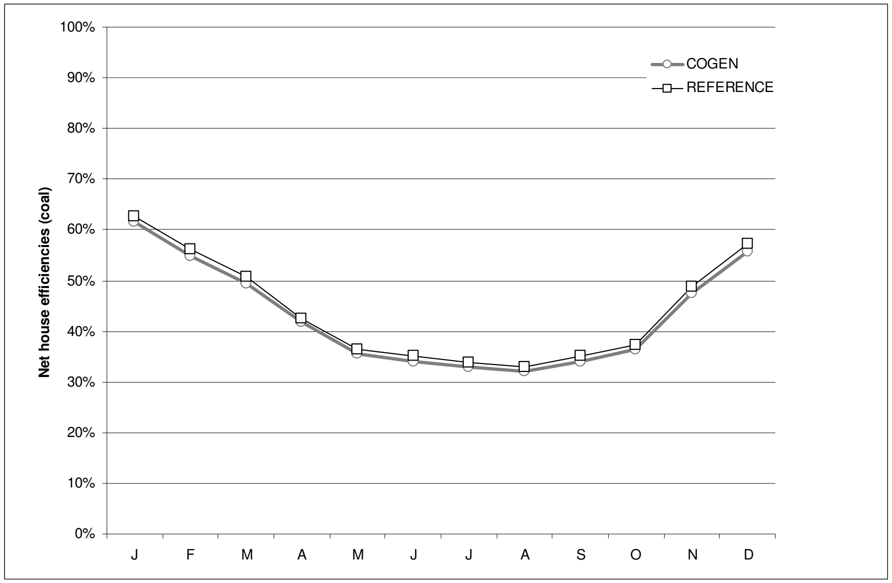
CASE ***SE 100 H G2***

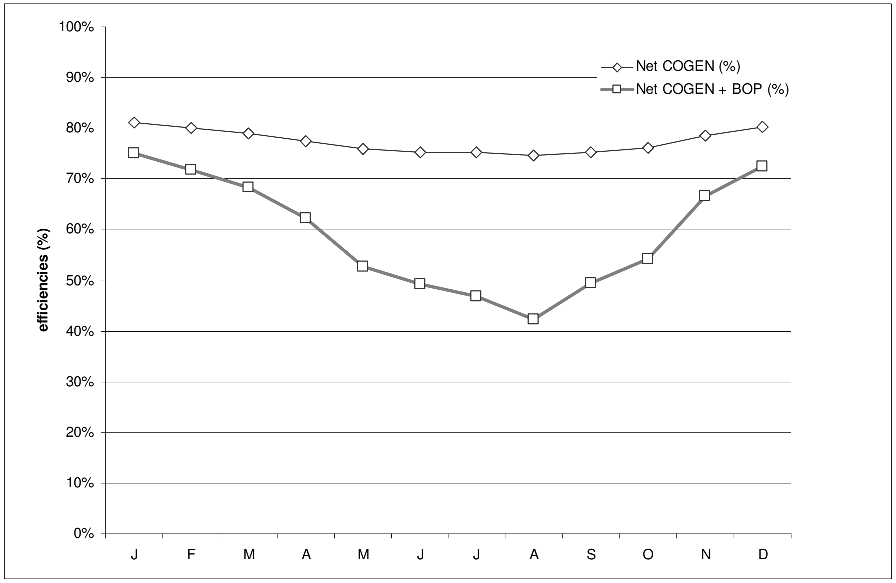
House	Average size, average construction
Electricity	Average demand – generated profile 2
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004

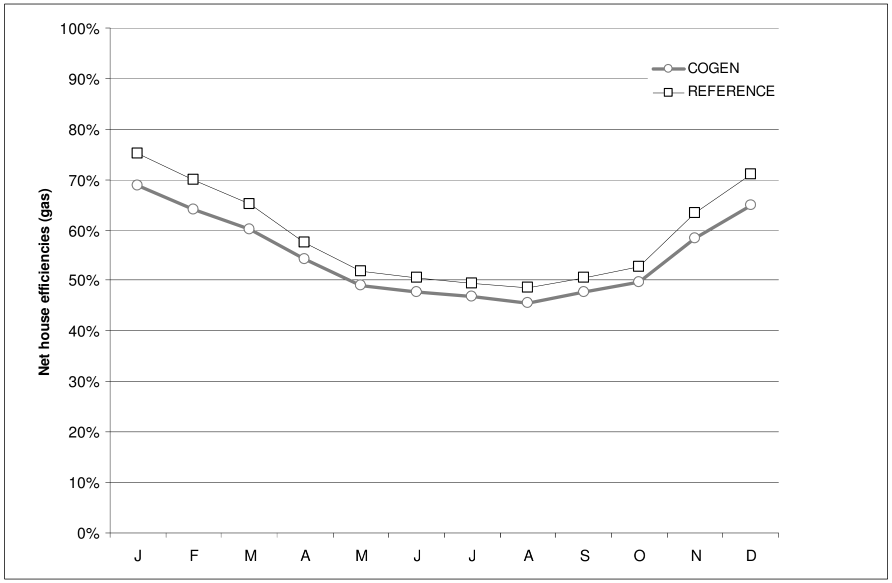


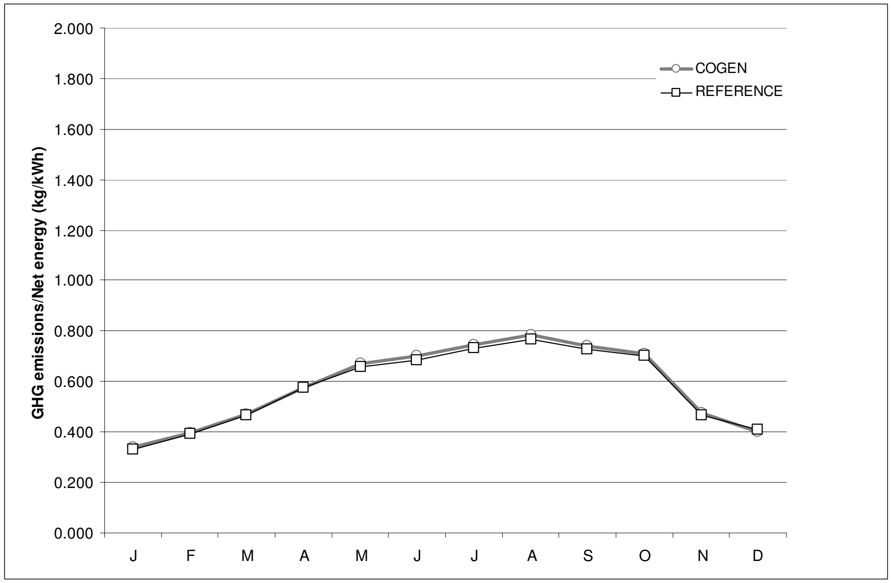
Annual summaries

Reference energy demand	20173 kWh
Simulated energy demand	20484 kWh (**+1.5%**)
GHG emissions	10259 kg CO_2 (**+1.3%**)
Emissions/energy	**0.509** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.9%
COGEN house	45.8% (**-1.2%-p.**)
	(gas fired grid)
Reference house	62.1%
COGEN house	57.6% gas (**-4.4%-p.**)
Grid reliance	+86.6%
COGEN + BOP efficiencies	
Net electric + heat	66.6%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%





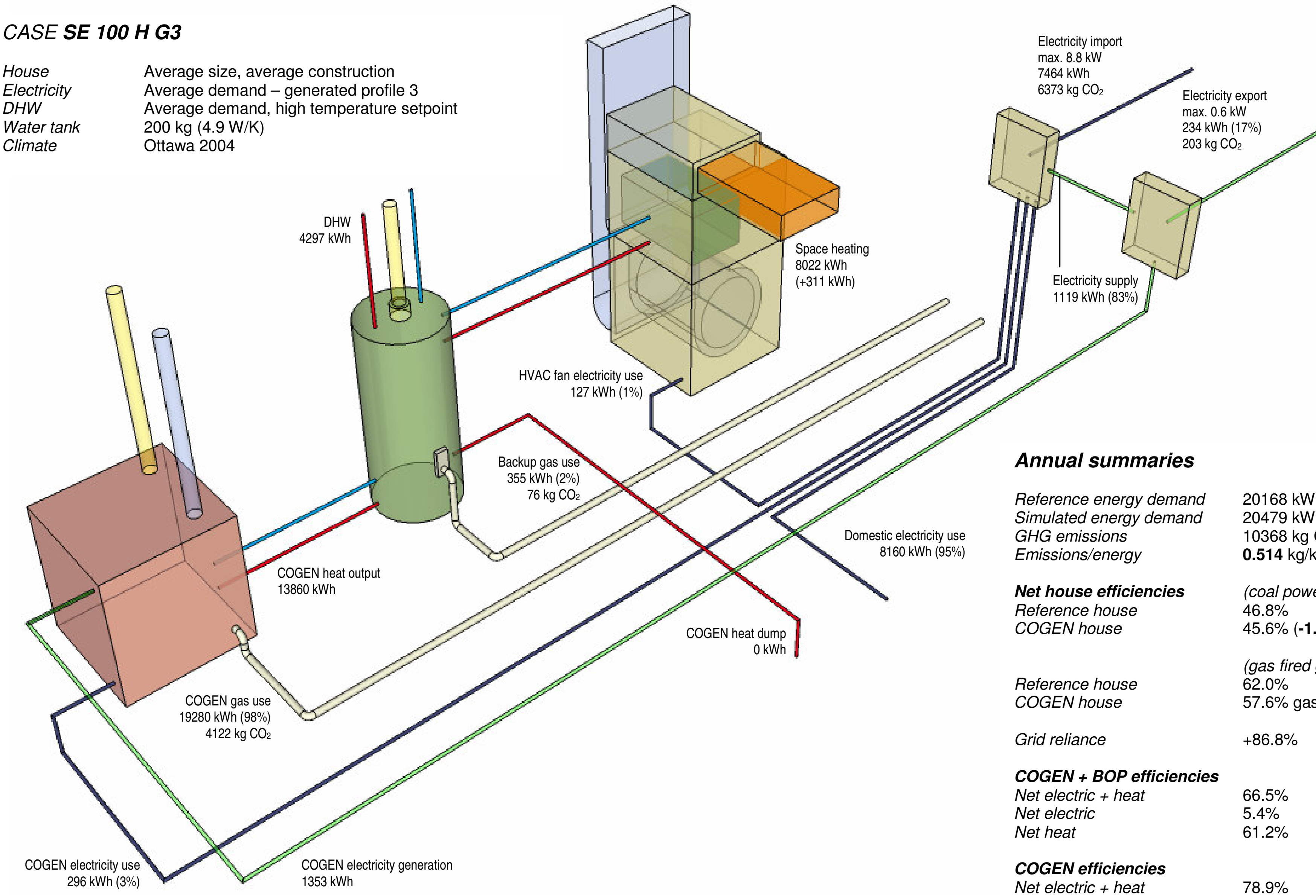




CASE SE 100 H G2 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

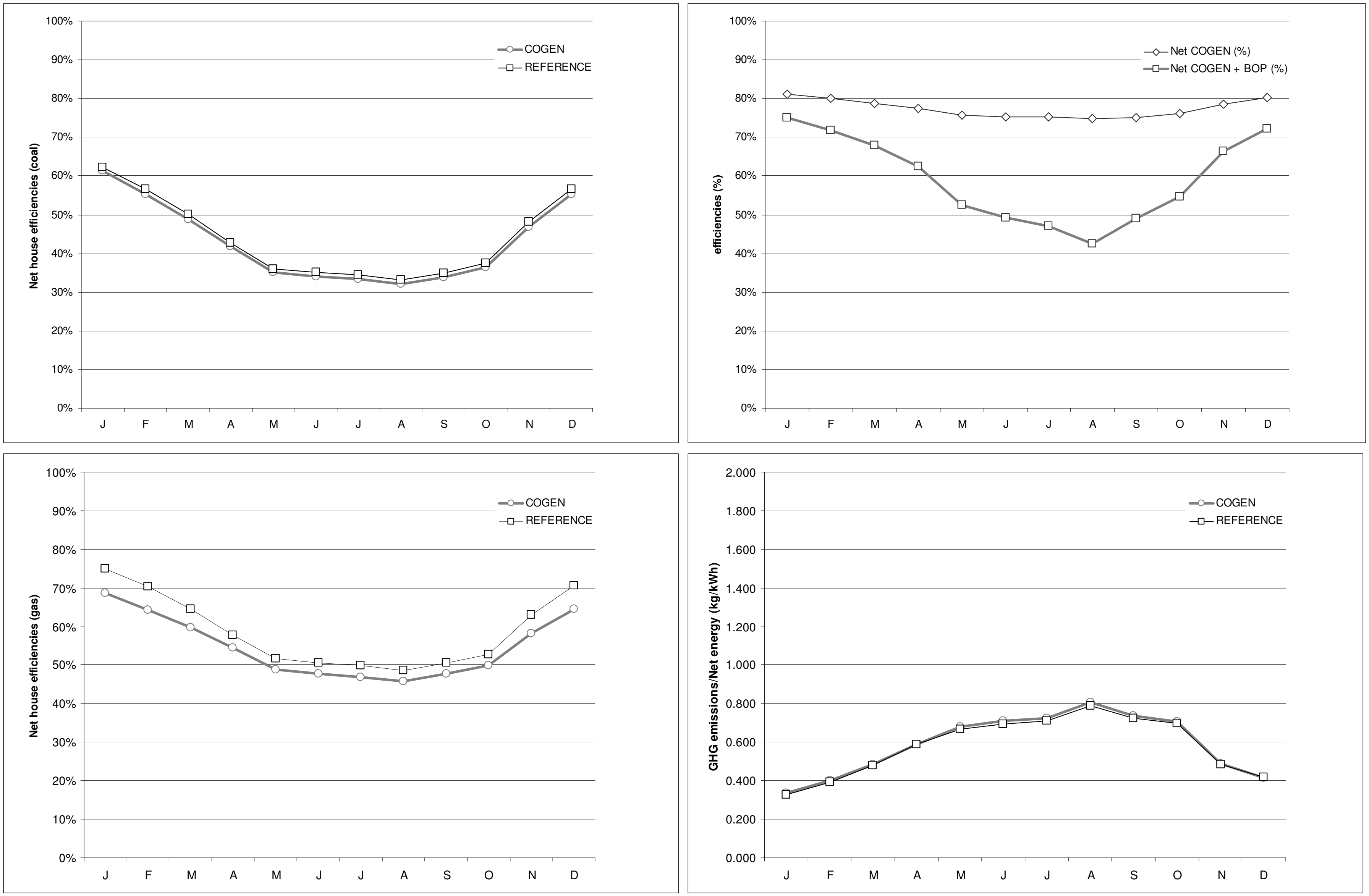
CASE ***SE 100 H G3***

House	Average size, average construction
Electricity	Average demand – generated profile 3
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

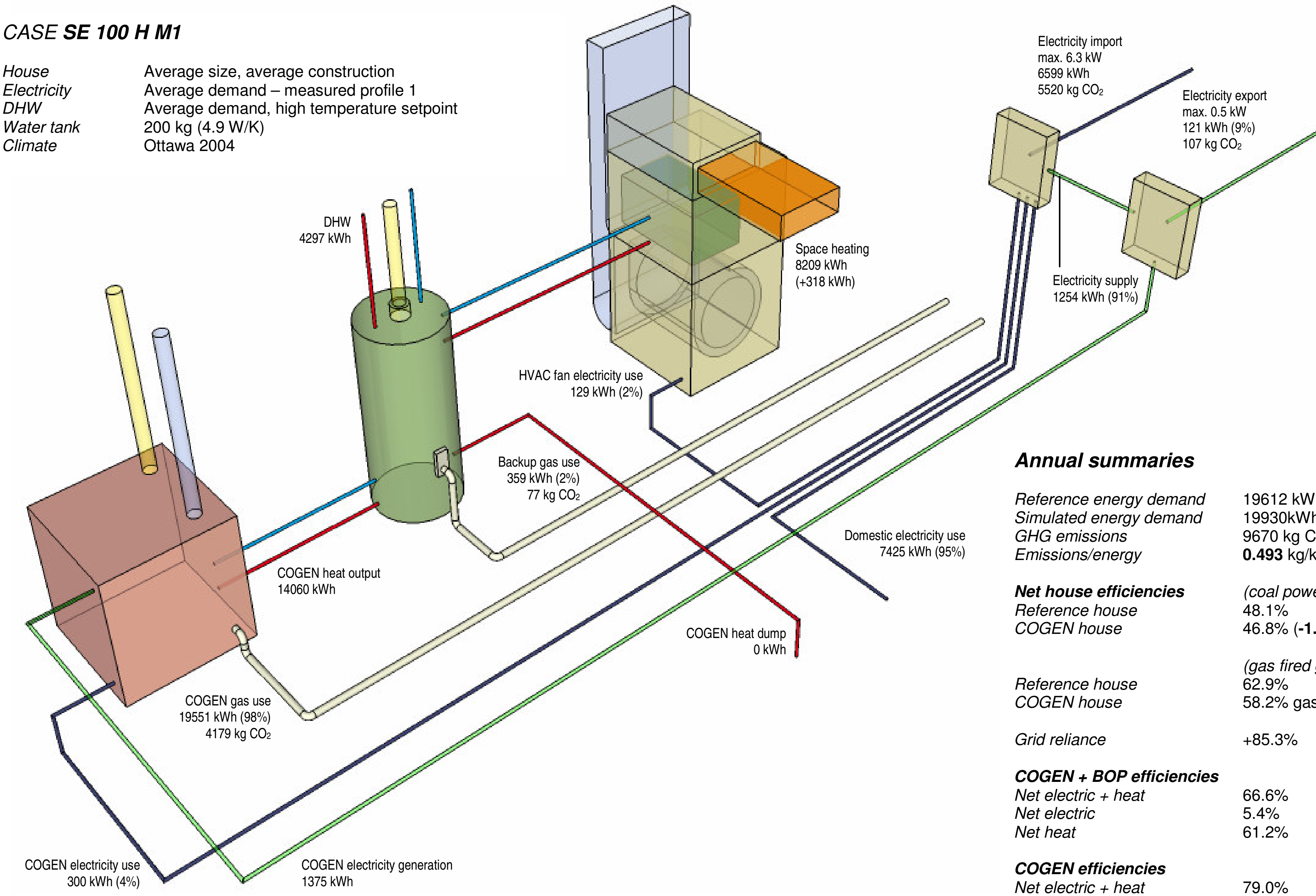
Reference energy demand	20168 kWh
Simulated energy demand	20479 kWh (**+1.5%**)
GHG emissions	10368 kg CO_2 (**+1.3%**)
Emissions/energy	**0.514** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.8%
COGEN house	45.6% (**-1.2%-p.**)
	(gas fired grid)
Reference house	62.0%
COGEN house	57.6% gas (**-4.4%-p.**)
Grid reliance	+86.8%
COGEN + BOP efficiencies	
Net electric + heat	66.5%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H G3 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

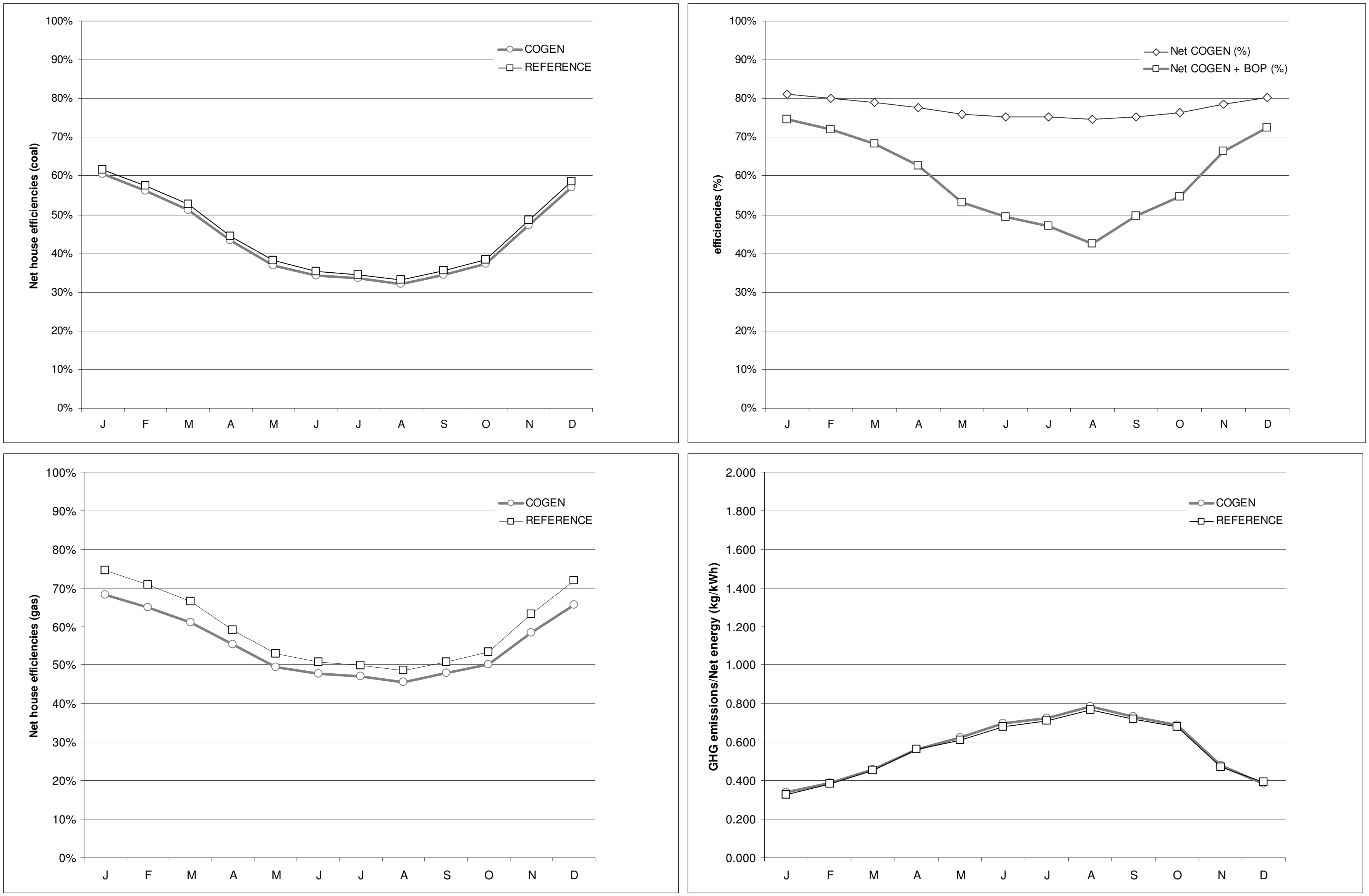
CASE ***SE 100 H M1***

House	Average size, average construction
Electricity	Average demand – measured profile 1
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

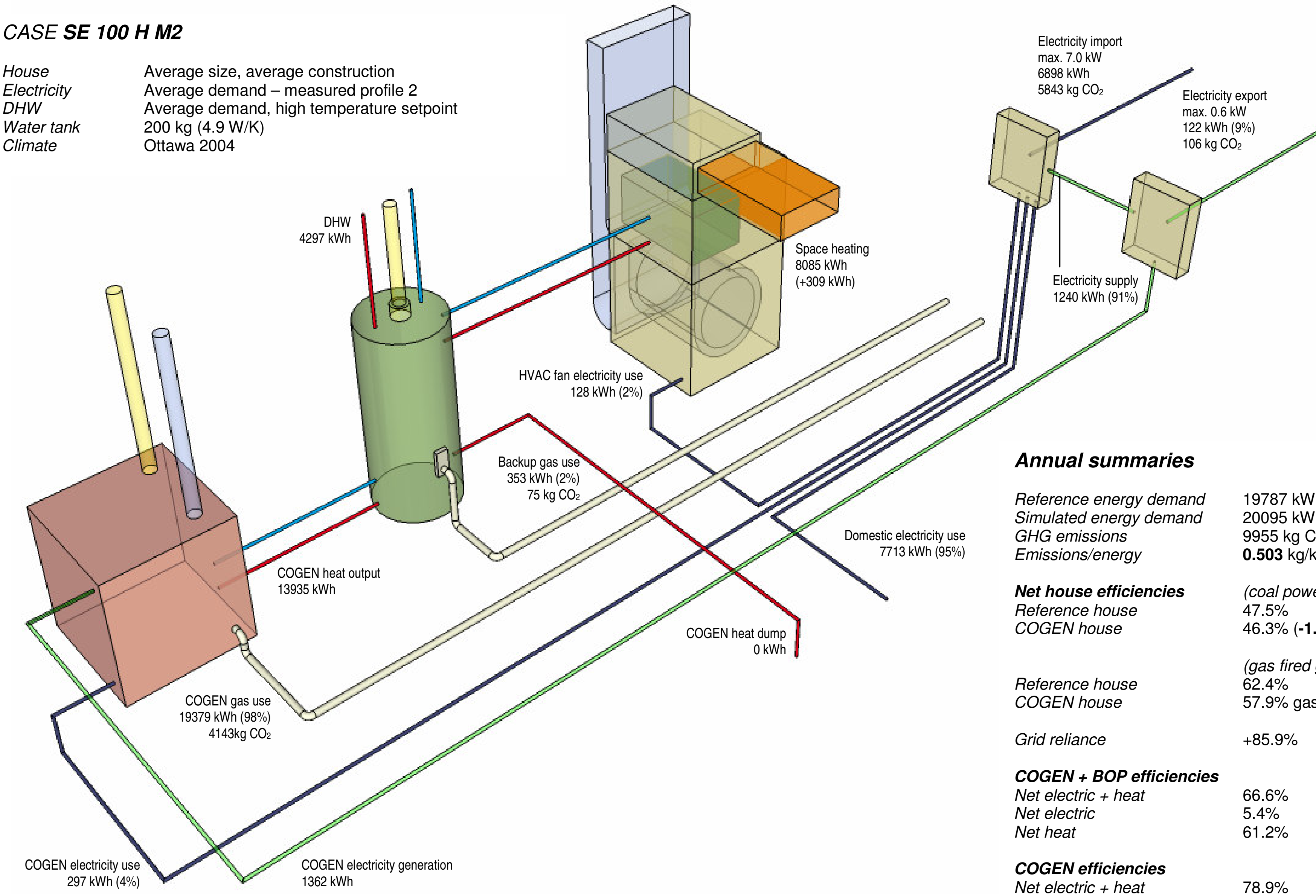
Reference energy demand	19612 kWh
Simulated energy demand	19930kWh (**+1.6%**)
GHG emissions	9670 kg CO_2 (**+1.3%**)
Emissions/energy	**0.493** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	48.1%
COGEN house	46.8% (**-1.3%-p.**)
	(gas fired grid)
Reference house	62.9%
COGEN house	58.2% gas (**-4.7%-p.**)
Grid reliance	+85.3%
COGEN + BOP efficiencies	
Net electric + heat	66.6%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	79.0%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H M1 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

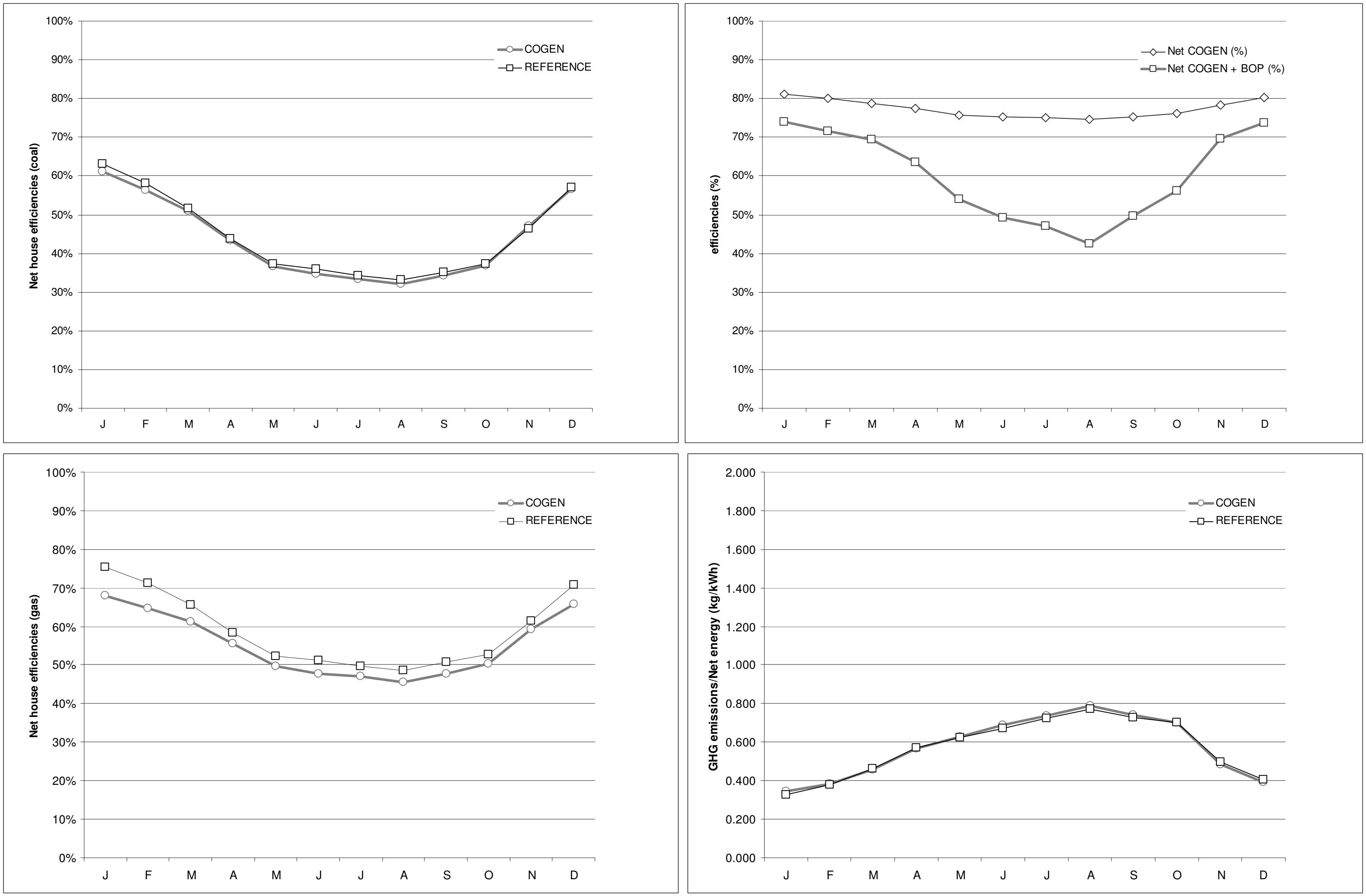
CASE ***SE 100 H M2***

House	Average size, average construction
Electricity	Average demand – measured profile 2
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

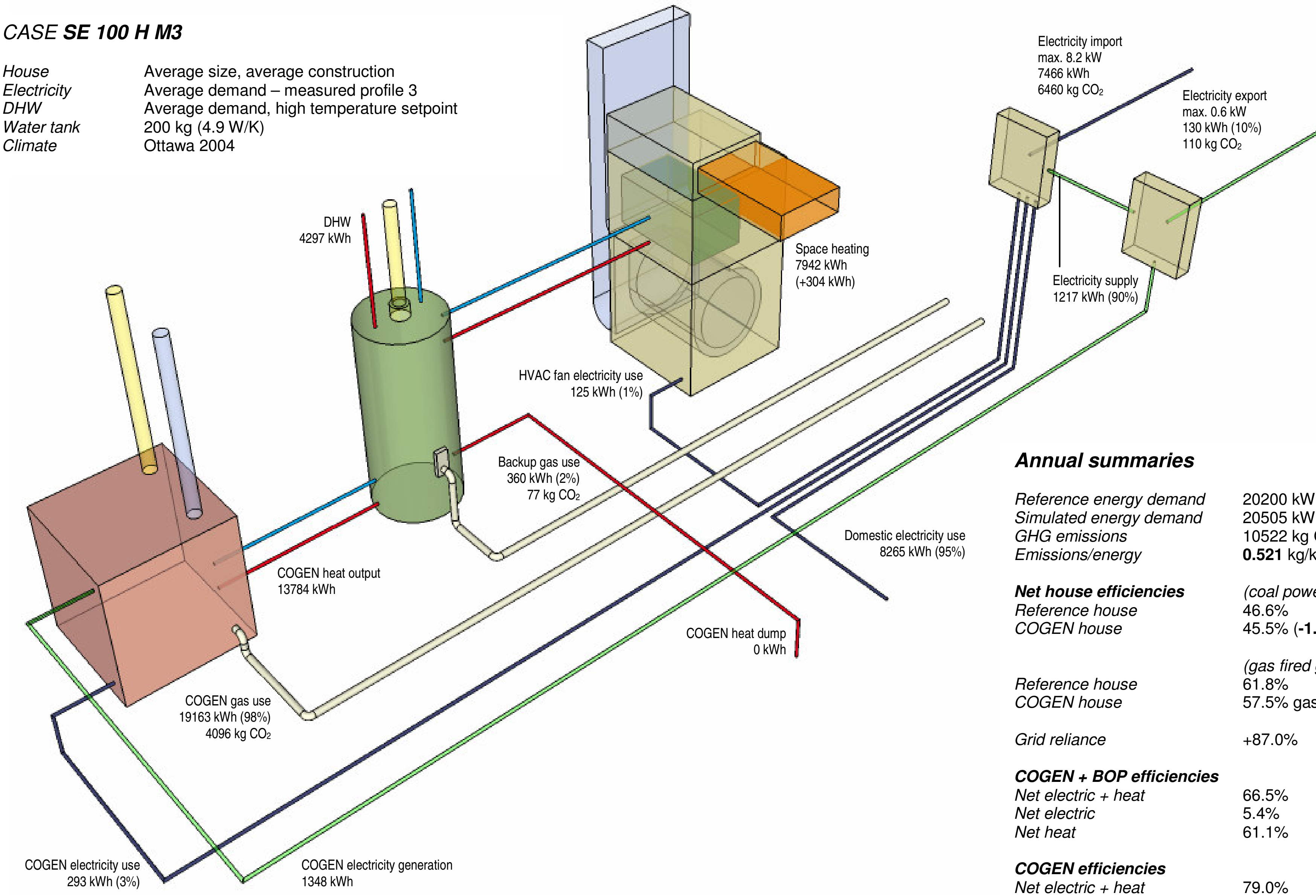
Reference energy demand	19787 kWh
Simulated energy demand	20095 kWh (**+1.6%**)
GHG emissions	9955 kg CO_2 (**+1.3%**)
Emissions/energy	**0.503** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	47.5%
COGEN house	46.3% (**-1.2%-p.**)
	(gas fired grid)
Reference house	62.4%
COGEN house	57.9% gas (**-4.5%-p.**)
Grid reliance	+85.9%
COGEN + BOP efficiencies	
Net electric + heat	66.6%
Net electric	5.4%
Net heat	61.2%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H M2 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

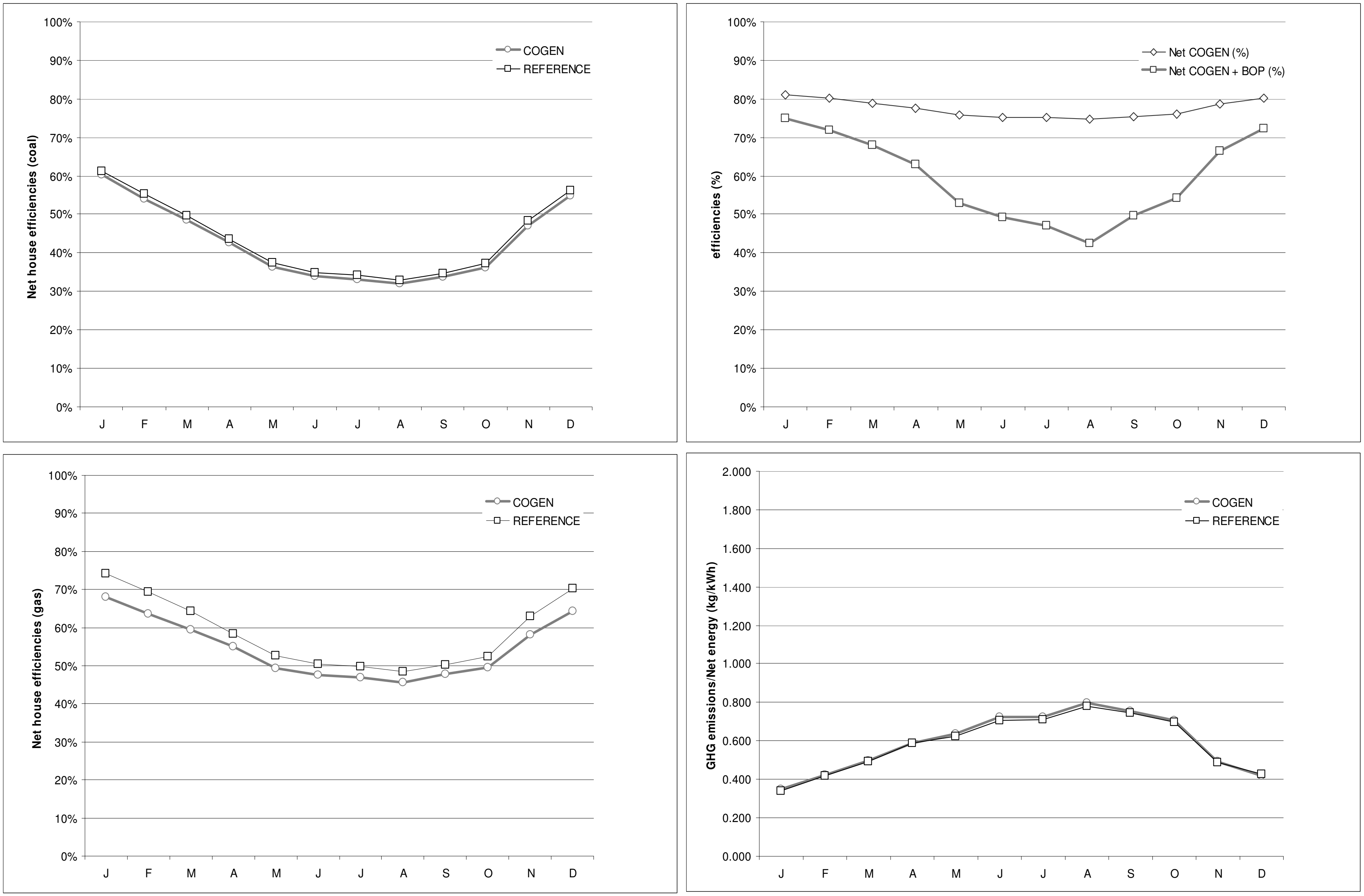
CASE ***SE 100 H M3***

House	Average size, average construction
Electricity	Average demand – measured profile 3
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

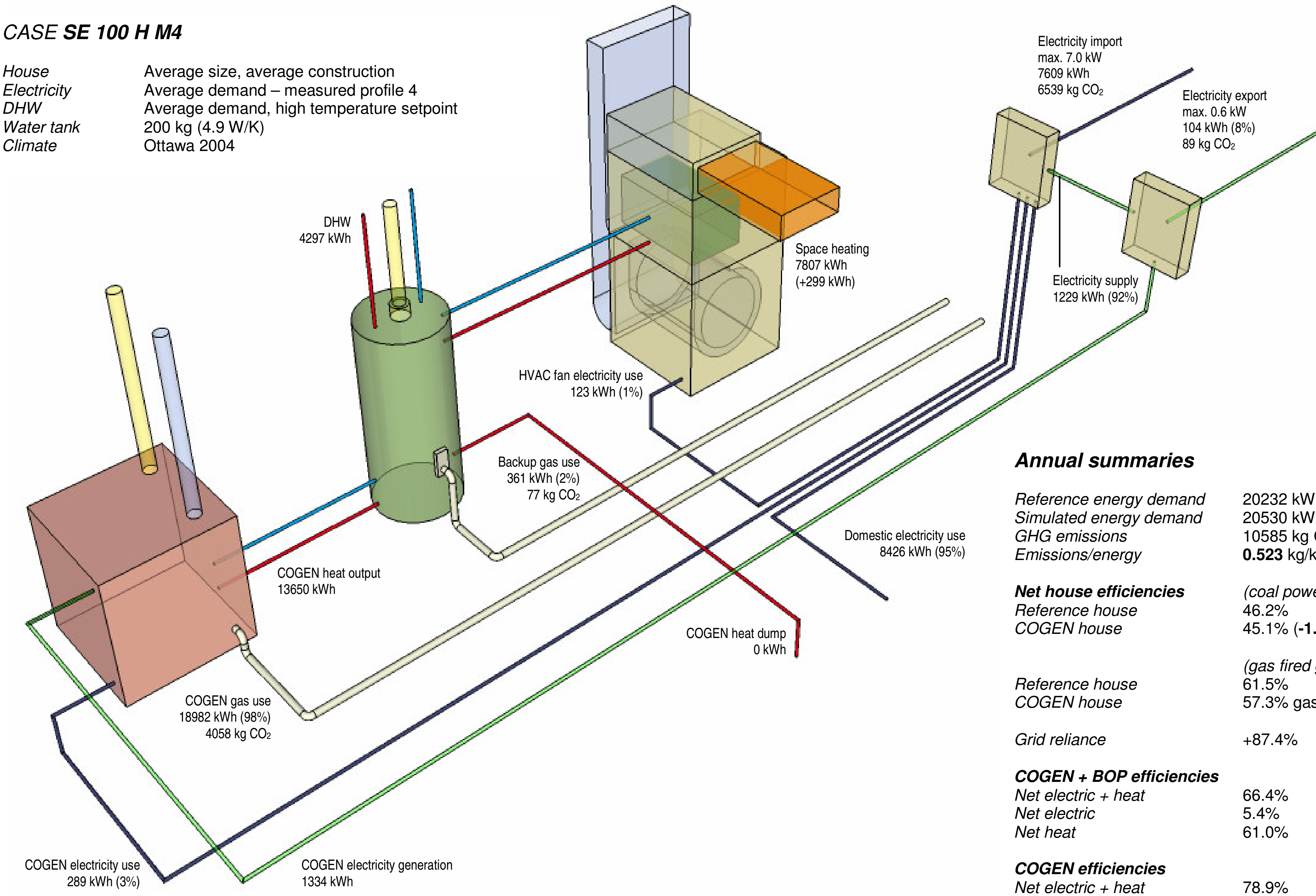
Reference energy demand	20200 kWh
Simulated energy demand	20505 kWh (**+1.5%**)
GHG emissions	10522 kg CO_2 (**+1.3%**)
Emissions/energy	**0.521** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.6%
COGEN house	45.5% (**-1.1%-p.**)
	(gas fired grid)
Reference house	61.8%
COGEN house	57.5% gas (**-4.3%-p.**)
Grid reliance	+87.0%
COGEN + BOP efficiencies	
Net electric + heat	66.5%
Net electric	5.4%
Net heat	61.1%
COGEN efficiencies	
Net electric + heat	79.0%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H M3 *Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.*

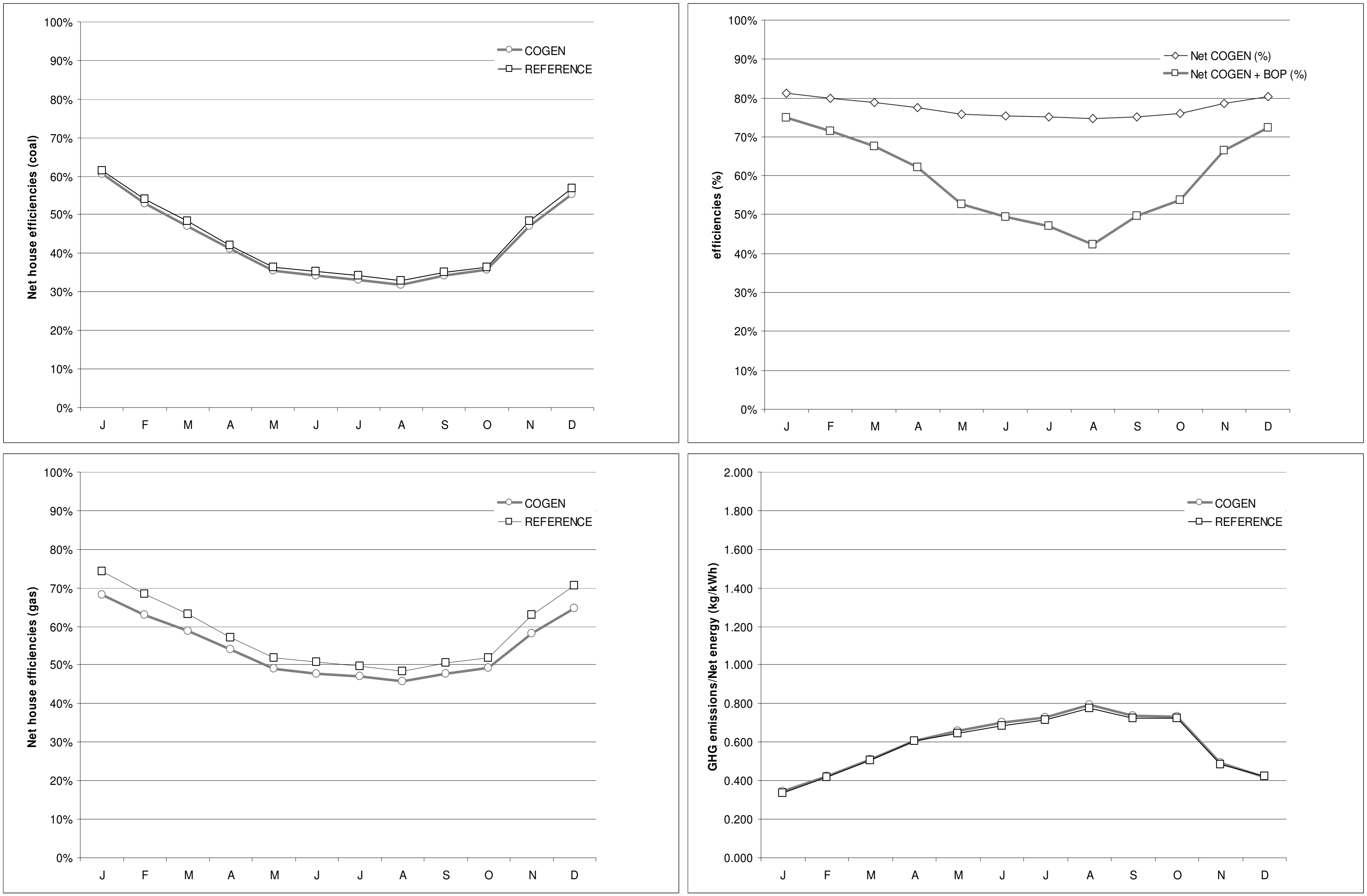
CASE ***SE 100 H M4***

House	Average size, average construction
Electricity	Average demand – measured profile 4
DHW	Average demand, high temperature setpoint
Water tank	200 kg (4.9 W/K)
Climate	Ottawa 2004



Annual summaries

Reference energy demand	20232 kWh
Simulated energy demand	20530 kWh (**+1.5%**)
GHG emissions	10585 kg CO_2 (**+1.3%**)
Emissions/energy	**0.523** kg/kWh
Net house efficiencies	*(coal powered grid)*
Reference house	46.2%
COGEN house	45.1% (**-1.1%-p.**)
	(gas fired grid)
Reference house	61.5%
COGEN house	57.3% gas (**-4.2%-p.**)
Grid reliance	+87.4%
COGEN + BOP efficiencies	
Net electric + heat	66.4%
Net electric	5.4%
Net heat	61.0%
COGEN efficiencies	
Net electric + heat	78.9%
Net electric	7.0%
Gross heat	71.9%
Net heat	71.9%
COGEN heat dump/output	0.0%



CASE SE 100 H M4

Top- and bottom-left primary energy house efficiencies (coal and natural gas, respectively); top-right: COGEN & COGEN + BOP efficiencies; bottom-right: COGEN GHG/energy ratios.