**Fixed Variables and Parameters**

*AP,i* capitalannualization rate for annualization period *P* and interest rate *i*

ancillary services cost (operating reserves) [$/MW]

battery storage energy capital cost [$/MWh]

battery storage power capital cost [$/MW]

wind collection capital cost in region *r* [$/MW-mi]

existing transmission and capacity cost [$]

gas turbine capital cost in region *r* [$/MW]

gas turbine ramping cost [$/MW]

Hydro-Quebec imported electricity cost in region *r* [$/MWh]

hydrogen storage energy capital cost [$/MWh]

hydrogen storage power capital cost [$/MW]

natural gas fuel cost in region *r* [$/MWh]

onshore wind power capital cost [$/MW]

offshore wind power capital cost [$/MW]

operational reserve cost [$/MW-h]

solar generation capital cost [$/MW]

capital cost of upgraded transmission from region *r* to adjacent region *r’*

[$/MW-mi]

existing hourly electricity demand in region *r* [MW]

additional average hourly electric vehicle demand in region *r* [MW]

additional average hourly electrified heating demand in region *r* [MW]

distance between region *r* and adjacent region *r’* [mi]

distance between the centroid of installed wind capacity and the capital city in region *r* [mi].

fixed hydropower electricity generation in region *r* [MW]

total monthly hydropower electricity generation in region *r* (fixed plus flexible) [MW]

electric vehicle charging duration [hours]

electric vehicle charging start time

minimum number of hours required for full daily electric vehicle charging

Hydro-Quebec electricity import limit in region r [MW]

interest rate

existing gas turbine capacity in region *r* [MW]

existing transmission flow limit between region *r* and adjacent region *r’* [MW]

transmission loss rate (constant for all transmission interfaces)

nuclear-generated electricity in region *r* [MW]

annualization period [years]

low-carbon electricity generation target: Fraction of total demand that must be met by low-carbon energy (combined nuclear, wind, water, and solar power)

set of all regions in study area

total number of hourly time steps in analysis (T = 52608 for 6-year period simulated)

potential offshore wind-generated electricity [dimensionless, MWgeneration/MWinstalled]

potential onshore wind-generated electricity [dimensionless, MWgeneration/MWinstalled]

potential solar-generated electricity [dimensionless, MWgeneration/MWinstalled]

fraction

electric vehicle charge rate under fixed charging constraints [MW]

battery storage efficiency

one-way electric vehicle charging efficiency

one-way hydrogen storage efficiency

minimum possible battery storage power-to-energy ratio

maximum possible battery storage power-to-energy ratio

minimum possible hydrogen storage power-to-energy ratio

minimum possible hydrogen storage power-to-energy ratio

κ storage self-discharge

σ net load reserve requirement

**Decision Variables**

aggregate battery storage state of charge [MWh]

aggregate hydrogen storage state of charge [MWh]

flexible hydropower electricity generation [MW]

net load [MW]

difference in net load between time steps *t* and *t-1* [MW]

utilized offshore wind-generated electricity [MW]

utilized onshore wind-generated electricity [MW]

utilized solar-generated electricity [MW]

imported electricity from Hydro-Quebec [MW]

battery storage energy capacity installed in region *r* [MWh]

battery storage power capacity installed in region *r* [MW]

new gas turbine capacity installed in region *r* [MW]

hydrogen storage energy capacity installed in region *r* [MWh]

hydrogen storage power capacity installed in region *r* [MW]

capacity of offshore wind generation installed in region *r* [MW]

capacity of onshore wind generation installed in region *r* [MW]

capacity of solar generation installed in region *r* [MW]

capacity of new transmission from region *r* to adjacent region *r’* [MW]

energy transmitted from region *r* to adjacent region *r’* [MW]

increase in battery storage state of charge [MW]

decrease in battery storage state of charge [MW]

increase in hydrogen storage state of charge [MW]

decrease in hydrogen storage state of charge [MW]

electric vehicle charge rate under flexible charging constraints [MW]

**Subscripts and Superscripts**

*batt* battery storage

*daily* daily

*diff* difference

*ev* electric vehicle

*exist* existing

*gt* gas turbine

*heat* electrified heating

*hq* Hydro-Quebec

*h2* hydrogen storage

day index (ranges between 0 and )

*max* maximum

*monthly* monthly

*off* offshore wind

*on* onshore wind

*p2e* power-to-energy

*r* region

*r’* region adjacent to *r*

*solar* solar

*t* hourly time step

*trans* transmission

**Constraints and Expressions**

Objective function:

(1)

Net load constraint:

(2)

Available generation constraints:

(3)

(4)

(5)

Renewable generation capacity constraints:

(6)

(7)

(8)

(9)

Hydropower generation constraints:

(12)

(13)

(14)

(15)

Storage energy balance constraints:

(16)

(17)

Storage power and energy capacity constraints:

(18)

(19)

(20)

(21)

(22)

(23)

Storage power-to-energy ratio constraints:

(24)

(25)

Gas turbine constraints:

(26)

(27)

Transmission constraints:

(28)

(29)

Fixed electric vehicle charging constraint:

(30)

Flexible electric vehicle charging constraints:

(31)

(32)

Low-carbon electricity supply constraint

(33)

Renewable electricity supply constraint:

(34)

Supplementary cost equations:

(35)

(36)

Domain constraint:

(37)

Capital cost annualization equation:

* All costs described as ‘capital costs’ in the nomenclature are annualized using a technology-specific *AP,i* annualization rate and the number of years simulated.

(38)