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Sustainable convergence of electricity and transport sectors in the context of a hydrogen economy

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ABSTRACT

This paper analyzes the electricity and transport sectors within a single integrated framework and presents the capabilities of this integrated approach to realize an environmentally and economically sustainable transport sector based on fuel cell vehicles (FCVs). A comprehensive robust optimization planning model for the transition to FCVs is developed, considering the constraints of both electricity and transport sectors. This model is finally applied to the real case of Ontario, Canada to determine the Ontario's grid potential to support these vehicles in the transport sector for a planning horizon ending in 2025. With a reasonable trade-off between optimality and conservatism, it is found that more than 170,000 FCVs can be introduced into Ontario's transport sector by 2025 without jeopardizing the reliability of the system or any additional grid investments such as new power generation and transmission installations.

1. Introduction

1.1. *Motivation*

The transport sector is one of the largest and fastest growing contributors to both energy demand and greenhouse gases; for example, in Canada, the transport sector represents almost 35% of the total energy demand and is the second highest source of greenhouse gas emissions [1,2]. In view of these facts and the challenges associated with the supply of oil, the issue of alternative fuels for meeting the future energy demand of the transport sector has gained notable attention.

Abbreviations: AFV, alternative-fuel vehicle; FCV, fuel cell vehicle; GV, gasoline vehicle; HHV, higher heating value; HOEP, hourly ontario energy price; HPP, hydrogen production plant; IESO, independent electricity system operator; LDV, light-duty vehicle; MILP, mixed integer linear programming; NE, northeast; NW, northwest; SCC, social cost of carbon; SW, southwest.

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Nomenclature

Indices

c	index for vehicle type
e	index for constraint under uncertainty
i, j	index for zones
l	index for voltage angle block
m	index for Monte Carlo simulation
v	index for uncertain parameter
y, k	index for year
τ, ω	index for time period
ω_1	index for the time period corresponding to weekday hours
ω_2	index for the time period corresponding to weekend hours

Sets

E	set of constraints subject to uncertainty
L_1	set of total voltage angle blocks; $L_1 = \{1, \ldots, L\}$
L_2	set of voltage angle blocks; $L_2 = \{1, \ldots, L-1\}$
L_3	set of voltage angle blocks; $L_3 = \{2, \ldots, L\}$
L_4	set of voltage angle blocks; $L_4 = \{2, \ldots, L-1\}$
U	set of uncertainty
V	set of total uncertain parameters
V_e	set of uncertain parameters in constraint e
VT	set of different types of light-duty vehicles
X	set of mixed integer feasible solution
Y	set of planning years
Y_1	set of planning years excluding the first year
Z	set of zones
Z^*	set of hydrogen transfer corridors
Ψ	set of time periods; $\Psi = \{\omega_1, \omega_2\}$
Ω	set of transmission lines

Parameters

AM	annual mileage, km
b_{ijy}	line susceptance, p.u
CC_{cab}	capital cost of cab, CAD.
CC_{tube}	capital cost of tube trailers, CAD
Cf_y	correction factor
CF_{hpp}	average capacity factor of HPPs, %
$Chpp_{iy}$	local required capacity of HPPs, MW
$\overline{CT}$	maximum capacity of each compressed gas truck, ton
d_{ij}	approximate distance between zones, km
DR	discount rate, %.
E_{CO_2}	constant value of CO_2 emissions from burning gasoline, kg/liter
ER_{chp_i}	emission rate of CHP plants, ton/MWh
ER_{coal_i}	emission rate of coal plants, ton/MWh
FE_{fcv}	fuel economy of the fuel cell vehicle, km/kg
$FE_{gv_{cy}}$	fuel economy of the gasoline vehicle, km/liter
g_{ijy}	line conductance, p.u.
h	number of off-peak hours
h_{wd}	number of HPPs operation hours in weekdays
h_{we}	number of HPPs operation hours in weekends
H	last year of the planning horizon
HHV	higher heating value of hydrogen, kWh/kg
L	total number of voltage angle blocks
LF	linking factor, ton/day MW
LT_{cab}	lifetime of cab, year
LT_{tube}	lifetime of tube trailer, year
M	number of Monte Carlo simulations
$Nldv_{iy}$	total number of light-duty vehicles
OC_y	operation cost of compressed gas truck, CAD/km
p_e	threshold probability of constraint e
P_{e_y}	total base-load electricity demand, MW
$P^{\tau}_{e_{iy}}$	zonal base-load electricity demand, MW
$\overline{P_{g_{iy}}}$	maximum available generation power, MW
$\underline{P_{giy}}$	lower bound of zonal generation power, MW
$\overline{P_{ga_{iy}}}$	maximum capacity of non-polluting generation resources, MW
$\overline{P_{gb_{iy}}}$	maximum capacity of non-polluting plus CHP generation resources, MW
$\overline{P_{hpp_{iy}}}$	maximum size of HPPs, MW
$\overline{P_{miy}}$	upper bound of imported power, MW
$\underline{P_{miy}}$	lower bound of imported power, MW
$\overline{P_{xiy}}$	upper bound of exported power, MW
$\underline{P_{x_{iy}}}$	lower bound of exported power, MW
$\overline{Pd}_{ijy}$	maximum capacity of transmission corridor for direct power flow, MW
$\overline{Pr}_{ijy}$	maximum capacity of transmission corridor for reverse power flow, MW
PS	planning span, year
s_{ev}	scaled deviation
S_{cab_y}	salvage value of cab (% of initial cost)
S_{tube_y}	salvage value of tube trailer (% of initial cost)
$SC_{CO_2}p$	social cost of CO_2 emission in the population area, CAD/ton
$SC_{CO_2}g$	social cost of CO_2 emission of generation, CAD/ton
$\overline{TH}$	upper bound of transferred hydrogen, ton/day
$\underline{TH}$	lower bound of transferred hydrogen, ton/day
VS_c	percent share of vehicle
y_1	first year of the planning horizon
$\alpha_{ijy}(l)$	slope of the lth block of voltage angle, MW/rad
Γ_e	budget of uncertainty
$\Delta\delta_y$	upper bound of each angle block, rad
$\Delta\eta_{hpp}$	efficiency improvement of the HPPs over the planning horizon
$\overline{\Delta P_{hpp_{iy}}}$	maximum annual development of HPPs, MW
ϵ_a, ϵ_b	small positive numbers
ϵ_t	constraint violation probability, %
η^b_{hpp}	base efficiency of HPPs at the beginning of the planning horizon
λ	a random parameter following a normal distribution with zero mean and unit standard deviation
$\overline{\mu}_y$	maximum possible FCV penetration, %
π_y	internal or hourly Ontario energy price, CAD/MWh
π_{m_y}	import electricity price, CAD/MWh
π_{x_y}	export electricity price, CAD/MWh
ρ	size of the relative perturbation, %

Variables

FF_{iy}	feasibility factor