OPTIMUM DESIGN OF SOLAR PHOTOVOLTAIC BASED HYDROGEN ENERGY SYSTEM FOR MACRO AND MICRO DISTRIBUTION

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ABSTRACT

With the growing concerns on energy security and climate change, it is crucial to develop a more sustainable energy system before fossil fuel reserves are depleted or global warming impacts the environment more critically. Hydrogen has been regarded as the fuel of the future as it possesses numerous benefits as an energy carrier. Producing hydrogen using renewable energy through electrolysis process allows the yield of low-carbon hydrogen with minimum carbon footprint. Malaysia receives abundant sunshine throughout the year and hence the feasibility of solar-based electrolytic hydrogen generation is worth investigation. Considering the potential uses of hydrogen as transportation fuel, energy storage, and secondary electricity supply, this study aimed to develop a holistic framework for the optimization of a solar photovoltaic based, integrated hydrogen-electricity supply system based on micro and macro level plannings. Micro-planning of hydrogen energy system allows it to be designed in greater details but the allocation of resources within networks is usually not considered. The following models have been proposed in this thesis for micro-level planning of hydrogen energy system: i) mathematical model to optimize solar panel orientation for maximum solar radiation yield, ii) mathematical model to optimize a single-site hydrogen-electricity supply system based on the average day energy profile, and iii) mathematical model to optimize a single-site hydrogen-electricity supply system based on annual hourly energy profiles to consider the intermittency of renewables. Meanwhile, macro-level optimization of hydrogen-electricity supply system provides a bigger picture by designing the optimal hydrogen-electricity supply chain at regional, state or country level. In such cases, geographical conditions should be taken into account when determining the optimal locations and capacities of supply chain infrastructures. The final model proposed in this work represents a spatial optimization framework for multi-site hydrogen-electricity supply chain. Spatial optimization integrates spatial considerations into optimization model which provides powerful tools for location-allocation modelling, land-use planning, and urban design. This allows the determination of optimal supply chain configuration and transportation of products from one site to another. For this study, MATLAB and GAMS have been used for mathematical optimization, while ArcGIS was adopted for spatial analysis. Case study results indicated that the installation of solar tracking system could improve the solar radiation yield up to 22.41% and reduce the cost of microgrid by 7.2%. Furthermore, 32 to 55% of cost reduction was observed when only 95% of the loads were targeted in microgrid. Moreover, the total investment cost of an integrated hydrogen-electricity supply network in Johor was found to be 13.5 billion USD/y. Overall, a systematic framework for the optimization of hydrogen energy system had been developed and demonstrated in this study. For future work, more variety of energy sources should be considered for hydrogen production and the scope of study should be extended to whole Malaysia for a full picture of hydrogen energy system in this country.

ABSTRAK

Dengan keprihatinan yang semakin meningkat mengenai keselamatan tenaga dan perubahan iklim, pembangunan sistem tenaga yang lebih lestari adalah sangat penting sebelum simpanan bahan bakar fosil habis atau pemanasan global mempengaruhi alam sekitar dengan lebih kritikal. Hidrogen telah dianggap sebagai bahan bakar masa depan kerana ia mempunyai banyak manfaat sebagai pembawa tenaga. Penghasilan hidrogen menggunakan tenaga yang boleh diperbaharui melalui proses elektrolisis dapat menghasilkan hidrogen rendah karbon dengan jejak karbon minimum. Malaysia mempunyai cahaya matahari yang melimpah sepanjang tahun dan kemungkinan penjanaan hidrogen elektrolitik berasaskan solar seharusnya disiasat. Dengan potensi penggunaan hidrogen sebagai bahan bakar pengangkutan, penyimpanan tenaga, dan bekalan elektrik sekunder, kajian ini bertujuan untuk membangunkan kerangka kerja yang holistik untuk pengoptimuman sistem bekalan hidrogen-elektrik bersepadu yang berasaskan solar fotovoltaik berdasarkan perancangan pada tahap mikro dan makro. Perancangan sistem bekalan hidrogen-elektrik pada tahap mikro membenarkannya dirancang dengan lebih terperinci tetapi peruntukan sumber dalam rangkaian tidak dipertimbangkan. Model berikut telah diusulkan dalam kerja penyelidikan ini untuk perancangan sistem bekalan hidrogen-elektrik pada tahap mikro: i) model matematik untuk mengoptimumkan halaan panel solar supaya mendapatkan hasil sinaran suria yang maksimum, ii) model matematik untuk mengoptimumkan sistem bekalan hidrogen-elektrik pada satu tempat berdasarkan profil tenaga purata, dan iii) model matematik untuk mengoptimumkan sistem bekalan hidrogen-elektrik pada satu tempat berdasarkan profil tenaga setahun untuk mempertimbangkan turun naik bekalan tenaga boleh diperbaharui. Sebaliknya, pengoptimuman sistem bekalan hidrogen-elektrik pada tahap makro memberikan gambaran besar dengan perancangan rantaian bekalan yang optimum di peringkat wilayah, negeri atau negara. Oleh itu, keadaan geografi harus dipertimbangkan ketika menentukan kapasiti dan lokasi infrastruktur rantaian bekalan yang optimum. Model terakhir dalam kerja penyelidikan ini adalah model pengoptimuman spasial untuk rantaian bekalan hidrogen-elektrik pelbagai tempat. Pengintegrasian pertimbangan spasial ke dalam model pengoptimuman mempermudahkan pemodelan peruntukan lokasi, perancangan penggunaan tanah, dan reka bentuk bandar. Ini memungkinkan penentuan konfigurasi rantaian bekalan yang optimum, serta peruntukan produk antara pelbagai tempat. Untuk kajian ini, MATLAB dan GAMS telah digunakan untuk pengoptimuman matematik, sementara ArcGIS digunakan untuk analisis spasial. Keputusan kajian kes menunjukkan bahawa pemasangan sistem pengesan suria dapat meningkatkan hasil sinaran suria sehingga 22.41% dan mengurangkan kos mikrogrid sebanyak 7.2%. Tambahan pula, pengurangan kos sebanyak 32 hingga 55% telah diperhatikan apabila hanya 95% daripada permintaan tenaga disasarkan oleh mikrogrid. Selain itu, jumlah kos pelaburan yang diperlukan untuk membina rangkaian bekalan hidrogen-elektrik di Johor adalah sebanyak 13.5 bilion dolar Amerika setahun. Secara keseluruhannya, rangka kerja yang sistematik untuk pengoptimuman sistem tenaga hidrogen telah dibangunkan dan ditunjukkan dalam kajian ini. Untuk kerja pada masa depan, penghasilan hidrogen dengan pelbagai sumber tenaga perlu dipertimbangkan dan skop kajian perlu diperluaskan ke seluruh Malaysia untuk mendapatkan gambaran penuh sistem tenaga hidrogen di negara ini.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
AFOLU	-	Agriculture, forestry and other land use
BUR3	-	Malaysia's Third Biennial Update Report
CH_4	-	Methane
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
DAT	-	Dual-axis tracking
DC	-	Direct current
DEG	-	Distributed energy generation
DHI	-	Diffuse horizontal irradiance
DNI	-	Direct normal irradiance
EMS	-	Energy management strategy
EPoPA	-	Extended-power pinch analysis
ESS	-	Energy storage system
EWSAT	-	East-west single-axis tracking
FiT	-	Feed-in-Tariff
FCEV	-	Fuel cell electric vehicle
FO	-	Fixed optimal tilt angle throughout the year
FS	-	Fixed horizontal position
GA	-	Genetic algorithm
GAMS	-	General algebraic modelling systems
GDP	-	Gross domestic product
GH_2	-	Gaseous hydrogen
GHG	-	Greenhouse gases
GIS	-	Geographic information system
H_2	-	Hydrogen
HESC	-	Hydrogen-electricity supply chain
HESS	-	Hydrogen-electricity supply system
HSC	-	Hydrogen supply chain
ICE	-	Internal combustion engine

IEA	-	International energy agency
IPPU	-	Industrial processes and product use
LH_2	-	Liquefied hydrogen
LP	-	Linear programming
LOHC	-	Liquid organic hydrogen carrier
LPSP	-	Loss of power supply possibility
LSS	-	Large Scale Solar
LULUCF	-	Land use, land-use change and forestry
MILP	-	Mixed-integer linear programming
MINLP	-	Mixed-integer nonlinear programming
MO	-	Fixed optimal tilt angle adjusted on monthly basis
NEM	-	Net Energy Metering
NLP	-	Nonlinear programming
NSGA-II	-	Non-dominated Sorting Genetic Algorithm
NSSAT	-	North-south single-axis tracking
O&M	-	Operating and maintenance
PEM	-	Polymer electrolyte membrane
PEWP	-	Potential energy waste possibility
POX	-	Partial oxidation
PSO	-	Particle swarm optimization
PV	-	Photovoltaic
REF	-	Renewable Energy Fund
REVB	-	Retired electric vehicle battery
R/P	-	Reserve-to-production
SO	-	Fixed optimal tilt angle adjusted on seasonal basis
SR	-	Steam reforming
TMY	-	Typical meteorological year
UNFCCC	-	United Nations Framework Convention on Climate Change
VSAT	-	Vertical single-axis tracking
WGS	-	Water-gas shift

LIST OF SYMBOLS

β	-	Tilt angle of solar panel fixed throughout a year
β_m	-	Tilt angle of solar panel for month *m*
β_p	-	Tilt angle of solar panel for period *p*
$\beta_{d,t}$	-	Tilt angle of solar panel at local time *t* on day *d*
$\Delta_{d,t}$	-	Brightness
δ_d	-	Solar declination angle
$\varepsilon_{d,t}$	-	Clearness index
$\gamma^{s}_{d,t}$	-	Solar azimuth angle
γ	-	Azimuth angle of solar panel fixed throughout a year
$\gamma_{d,t}$	-	Azimuth angle of solar panel at local time *t* on day *d*
$\omega_{d,t}$	-	Hour angle
ϕ	-	Latitude of the study location
ρ	-	Surface albedo
σ	-	Hourly self-discharge rate
$\theta_{d,t}$	-	Angle of incidence
$\theta^{z}_{d,t}$	-	Zenith angle
$a_{d,t}$	-	Coefficient for diffuse radiation equation in Perez model
$A_j^{Feasible}$	-	Feasible area for construction at region *j*
A^{PV}	-	Area of solar panel
A_j^{PV}	-	Area of solar panel in region *j*
AAKT	-	Annual average distance travelled by vehicle
B_c^{COMP}	-	Binary defining whether hydrogen needs compression to be converted into form *c*
B_c^{FC}	-	Binary defining the form of hydrogen *c* that can be used for fuel cell
B_c^{HYD}	-	Binary defining whether hydrogen needs hydrogenation to be converted into form *c*
B_c^{LIQ}	-	Binary defining whether hydrogen needs liquefaction to be converted into form *c*
B_c^{RF}	-	Binary defining the form of hydrogen *c* that can be used in refuelling station

$\mathrm{B}_{c}^{\mathrm{Pipe}}$	-	Binary defining the form of hydrogen *c* that can be transported with pipeline
$\mathrm{B}_{j,k}^{\mathrm{Trans}}$	-	Binary defining whether the product can be transported from region *j* to region *k*
$\mathrm{B}_{c}^{\mathrm{Truck}}$	-	Binary defining the form of hydrogen c that can be transported with trailer
$\mathrm{b}_{d,t}$	-	Coefficient for diffuse radiation equation in Perez model
B_{d}	-	Coefficient for equation of time calculation
B_{t}^{Ch}	-	Amount of energy chargeable into battery at time *t*
B_{t}^{Di}	-	Amount of energy dischargeable from battery at time *t*
B_{j}^{EImport}	-	Binary variable defining whether electricity is imported to region *j*
$B_{j}^{\mathrm{EHImport}}$	-	Binary variable defining whether electricity imported to region *j* is used to produce hydrogen
B_{j}^{EProd}	-	Binary variable defining whether electricity is produced in region *j*
B_{j}^{HImport}	-	Binary variable defining whether hydrogen is imported to region *j*
B_{j}^{HProd}	-	Binary variable defining whether hydrogen is produced in region *j*
B_{t}^{In}	-	Amount of energy charged into battery at time *t*
B_{t}^{Out}	-	Amount of energy discharged from battery at time *t*
BAT^{cap}	-	Battery capacity
BAT_{j}^{Cap}	-	Battery capacity in region *j*
BAT^{cost}	-	Battery annual cost
$\mathrm{BAT}^{\mathrm{DOD}}$	-	Battery depth of discharge
$\mathrm{BAT}^{\mathrm{ucapex}}$	-	Battery unit capital cost
$\mathrm{BAT}^{\mathrm{uopex}}$	-	Battery unit operating and maintenance cost
$\mathrm{BC}^{\mathrm{Eff}}$	-	Battery charging efficiency
$\mathrm{BD}^{\mathrm{Eff}}$	-	Battery discharging efficiency
BDL^{L}	-	Minimum allowable battery level
BDL^{U}	-	Maximum allowable battery level
$\mathrm{BS}^{\mathrm{Eff}}$	-	Battery storage efficiency
BSL	-	Battery level at the beginning
C^{annual}	-	Annual cost of system

$Cable^{\text{cost}}$	-	Power cable annual cost
$\text{Cable}^{\text{ucapex}}$	-	Power cable unit capital cost
Cable^{UL}	-	Maximum capacity of power cable
$\text{Cable}^{\text{uopex}}$	-	Power cable unit operating cost
$\text{COMP}^{\text{basecost}}$	-	Base cost of compressor (reference)
$\text{COMP}^{\text{basesize}}$	-	Base size of compressor (reference)
$COMP^{\text{cap}}$	-	Compressor capacity
$COMP^{\text{capex}}$	-	Compressor total capital cost
$COMP^{\text{cost}}$	-	Compressor annual cost
$\text{COMP}^{\text{loss}}$	-	Hydrogen losses in compressor
$COMP^{\text{opex}}$	-	Compressor annual operating cost
$\text{COMP}^{\text{opexrate}}$	-	The operating cost of compressor per unit capital cost
$COMP_{j,c}^{\text{power}}$	-	Compressor power requirement in region *j*
$COMP_{j,\text{c},tc}^{\text{range}}$	-	Throughput of compressor at capacity level tc in region *j*
$\text{COMP}_{tc}^{\text{range,UL}}$	-	Maximum limit of compressor with capacity level *tc*
$\text{COMP}^{\text{scalefactor}}$	-	Scale factor of compressor (reference)
$\text{COMP}^{\text{ucapex}}$	-	Compressor unit capital cost
$\text{COMP}_{tc}^{\text{ucapex}}$	-	Unit capital cost of compressor *tc*
$\text{COMP}^{\text{uopex}}$	-	Compressor unit operating cost
$\text{COMP}_{tc}^{\text{uopex}}$	-	Unit operating cost of compressor *tc*
$\text{COMP}_{c}^{\text{upower}}$	-	Unit power requirement to compress hydrogen to form *c*
$CONV_{j}^{\text{Cap}}$	-	Converter capacity in region *j*
$CONV^{\text{cost}}$	-	Converter annual cost
CONV^{Eff}	-	Converter efficiency
$\text{CONV}^{\text{ucapex}}$	-	Converter unit capital cost
$\text{CONV}^{\text{uopex}}$	-	Converter unit operating cost
$\text{Cost}^{\text{Extra}}$	-	Extra cost incurred to conventional fuel and electricity
CRF	-	Capital recovery factor
d	-	Day in a year
dp	-	Hydrogen pipeline of different diameters
$\text{D}_{j,k}$	-	Transportation distance between region *j* and region *k*

$\mathrm{D}^{\mathrm{Autonomy}}$	-	Days of autonomy
$\mathrm{Diesel}^{\mathrm{cost}}$	-	Diesel cost
E_{d}	-	Equation of time
E_t^{Debt}	-	Loads unsatisfied by the microgrid
$\mathrm{E}_j^{\mathrm{Demand}}$	-	Electricity demand in region *j*
$E_t^{\mathrm{DCDeficit}}$	-	Total energy deficits at time *t* expressed in the form of DC
E_t^{EDeficit}	-	Unfulfilled electrical load at time *t*
E_t^{EL}	-	Total amount of electricity delivered to electrolyzer at time *t*
$\mathrm{E}_t^{\mathrm{Eload}}$	-	Electricity demand in AC form at time *t*
E_t^{ELBAT}	-	Energy input from battery to electrolyzer to produce hydrogen for hydrogen load at time *t*
E_t^{ELP}	-	Energy input to electrolyzer to produce hydrogen for hydrogen load at time *t*
E_t^{ELS}	-	Energy input to electrolyzer to produce hydrogen for storage at time *t*
E_t^{FC}	-	Amount of energy input to fuel cell at time *t*
E_j^{FC}	-	Electricity produced in fuel cell in region *j*
E_j^{G}	-	Electricity generation from solar PV in region *j*
E_t^{HDeficit}	-	Unfulfilled hydrogen load at time *t*
$\mathrm{E}_t^{\mathrm{Hload}}$	-	Hydrogen demand in kWh at time *t*
$E_t^{\mathrm{HSDeficit}}$	-	Total energy deficits at time *t* expressed in the form of hydrogen
$E_t^{\mathrm{HStoHload}}$	-	Amount of hydrogen released from storage to satisfy the hydrogen load at time *t*
E_j^{Import}	-	Electricity imported to region *j*
$E_j^{\mathrm{ImporttoE}}$	-	Electricity imported to region *j* used for electricity demand
$E_j^{\mathrm{ImporttoH}}$	-	Electricity imported to region *j* used for hydrogen demand
E_t^{INV}	-	Net amount of electricity passing through inverter at time *t*
$\mathrm{E}^{\mathrm{losses}}$	-	Electricity losses during transmission and distribution
E_t^{Net}	-	Net amount of electricity ready to be stored at time *t*
E_t^{PV}	-	Amount of electricity produced in PV system at time *t*

E_j^{toDemand}	-	PV electricity produced in region *j* used to satisfy the electricity demand
E_j^{toE}	-	PV electricity produced in region *j* utilized in the form of electricity
$E_{j,k}^{\mathrm{toExport}}$	-	Electricity to exported from region *j* to region *k*
E_j^{toH}	-	PV electricity produced in region *j* used to synthesize hydrogen
E_j^{S}	-	Energy stored in battery
E_t^{ToBat}	-	Amount of electricity available for charging into battery at time *t*
E_t^{ToEL}	-	Amount of electricity available for electrolysis at time *t*
E_t^{Wasted}	-	Electricity produced by system at time *t* that is not used/stored
$\mathrm{ED}^{\mathrm{percapita}}$	-	Electricity demand per capita
EL^{cap}	-	Electrolyzer capacity
EL_j^{Cap}	-	Electrolyzer capacity in region *j*
EL^{cost}	-	Electrolyzer annual cost
$\mathrm{EL}^{\mathrm{Eff}}$	-	Electrolyzer efficiency
$\mathrm{EL}^{\mathrm{ucapex}}$	-	Electrolyzer unit capital cost
$\mathrm{EL}^{\mathrm{uopex}}$	-	Electrolyzer unit operating cost
$\mathrm{Elec}^{\mathrm{cost}}$	-	Grid electricity cost
$\mathrm{f}_{d,t}^{11}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}_{d,t}^{12}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}_{d,t}^{13}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}_{d,t}^{21}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}_{d,t}^{22}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}_{d,t}^{23}$	-	Statistically derived coefficients for ranges of clearness values
$\mathrm{f}^{\mathrm{Land}}$	-	Land-use factor based on the area of solar panel
$\mathrm{F}_{d,t}^{1}$	-	Brightness coefficient
$\mathrm{F}_{d,t}^{2}$	-	Brightness coefficient

FC^{cap}	-	Fuel cell capacity
FC_j^{Cap}	-	Fuel cell capacity in region *j*
FC^{cost}	-	Fuel cell annual cost
$\mathrm{FC}^{\mathrm{Eff}}$	-	Fuel cell efficiency
$\mathrm{FC}^{\mathrm{ucapex}}$	-	Fuel cell unit capital cost
$\mathrm{FC}^{\mathrm{uopex}}$	-	Fuel cell unit operating cost
$\mathrm{FCV}^{\mathrm{FE}}$	-	Fuel economy of fuel cell vehicle
$\mathrm{H}_j^{\mathrm{Demand}}$	-	Hydrogen demand in region *j*
H^{E}	-	Hydrogen energy content
H_j^{EImport}	-	Hydrogen produced from imported electricity at region *j*
$H_{j,c}^{\mathrm{Export}}$	-	Hydrogen in form *c* to be exported from region *j* to other regions
$H_{j,c}^{\mathrm{FC}}$	-	Hydrogen reacted in fuel cell in form *c* in region *j*
H_j^{G}	-	Hydrogen produced using local electricity at region *j*
$H_{j,c}^{\mathrm{Import}}$	-	Hydrogen in form *c* to be imported to region *j*
$H_{j,k,c}^{\mathrm{P}}$	-	Hydrogen transported using pipeline in form *c* from region *j* to region *k*
$H_{j,c}^{\mathrm{Pin.EIH}}$	-	Hydrogen produced using electricity imported to region *j* and to be converted into form *c*
$H_{j,c}^{\mathrm{Pin,LC}}$	-	Hydrogen produced using local electricity in region *j* and to be converted into form *c*
H^{PL}	-	Ratio of daily load to peak load
$H_{j,c}^{\mathrm{Pout,EIH}}$	-	Hydrogen produced using electricity imported to region *j* converted into form *c*
$H_{j,c}^{\mathrm{Pout,LC}}$	-	Hydrogen produced using local electricity in region *j* converted into form *c*
$H_{j,c}^{\mathrm{RF}}$	-	Hydrogen received at refuelling stations in form *c* in region *j*
$H_{j,c}^{\mathrm{S}}$	-	Amount of hydrogen stored in form *c* in region *j*
$H_{j,c}^{\mathrm{toSelf}}$	-	Hydrogen in form *c* to be used within region *j*
$H_{j,k,c}^{\mathrm{T}}$	-	Hydrogen transported using truck in form *c* from region *j* to region *k*
HDL^{L}	-	Minimum allowable hydrogen storage level
HDL^{U}	-	Maximum allowable hydrogen storage level

HS^{cap}	-	Hydrogen storage capacity
HS_t^{Ch}	-	Amount of energy chargeable into hydrogen tank at time *t*
HS^{cost}	-	Hydrogen storage annual cost
HS_t^{Di}	-	Amount of energy dischargeable from hydrogen tank at time *t*
HS^{kgcap}	-	Hydrogen storage capacity expressed in kg
HS_t^{OUT}	-	Hydrogen released to satisfy the loads under energy discharging scheme
$\text{HS}^{\text{ucapex}}$	-	Hydrogen storage unit capital cost
$\text{HS}_c^{\text{ucapex}}$	-	Hydrogen storage unit capital cost
HS^{uopex}	-	Hydrogen storage unit operating cost
$\text{HS}_c^{\text{uopex}}$	-	Hydrogen storage unit operating cost
HSL	-	Hydrogen storage level at the beginning
Hyd^{cost}	-	Hydrogenation annual cost
$Hyd_{j,th}^{\text{range}}$	-	Throughput of hydrogenation equipment at capacity level *th* in region *j*
$\text{Hyd}_{th}^{\text{range,UL}}$	-	Maximum throughput of hydrogenation equipment *th*
$\text{Hyd}_{th}^{\text{ucapex}}$	-	Unit capital cost of hydrogenation equipment *th*
$\text{Hyd}_{th}^{\text{uopex}}$	-	Unit operating cost of hydrogenation equipment *th*
i	-	Interest rate
I^{Annual}	-	Total solar radiation incident on the solar panel in a year
$\text{I}_{d,t}^{\text{Bn}}$	-	Direct normal irradiance
$I_{d,t}^{\text{Bp}}$	-	Direct beam radiation incident on solar panel at local time *t* on day *d*
$\text{I}_{d,t}^{\text{Dh}}$	-	Diffuse horizontal irradiance
$I_{d,t}^{\text{Dp}}$	-	Diffuse radiation incident on solar panel at local time *t* on day *d*
$\text{I}_{d,t}^{\text{e}}$	-	Extra-terrestrial radiation
$\text{I}_{d,t}^{\text{Gh}}$	-	Global horizontal irradiance
I_m^{Month}	-	Total solar radiation incident on the solar panel in a month
$I_{d,t}^{\text{Rp}}$	-	Reflected radiation incident on solar panel at local time *t* on day *d*

$I_{d,t}^{\mathrm{Total}}$	-	Amount of solar radiation incident on the solar panel at local time t on day d
INV^{cap}	-	Inverter capacity
INV^{cost}	-	Inverter annual cost
$\mathrm{INV}^{\mathrm{Eff}}$	-	Inverter efficiency
$\mathrm{INV}^{\mathrm{ucapex}}$	-	Inverter unit capital cost
$\mathrm{INV}^{\mathrm{uopex}}$	-	Inverter unit operating cost
Liq^{cost}	-	Liquefaction annual cost
$Liq_{j,tl}^{\mathrm{range}}$	-	Throughput of liquefaction equipment at capacity level *tl* in region *j*
$\mathrm{Liq}_{tl}^{\mathrm{range,UL}}$	-	Maximum throughput of liquefaction equipment *tl*
$\mathrm{Liq}_{tl}^{\mathrm{ucapex}}$	-	Unit capital cost of liquefaction equipment *tl*
$\mathrm{Liq}_{tl}^{\mathrm{uopex}}$	-	Unit operating cost of liquefaction equipment *tl*
$LCOE$	-	Levelized cost of energy
LONG	-	Longitude of the location
$LPSP$	-	Loss of power supply possibility
LT_{c}	-	Time for loading and unloading of hydrogen form *c* from trailers
LT_{t}	-	Local time
m	-	Month in a year
$\mathrm{m}_{d,t}$	-	Air mass
M	-	A dimensionless large number for the definition of binaries in MILP model
n_{d}	-	Day of the year
$N_{j,k}^{\mathrm{Cable}}$	-	Number of power cables transmitting electricity from region *j* to region *k*
$N_{j,c,tc}^{\mathrm{Comp}}$	-	Number of compressor at capacity level *tc* in region *j*
$N_{j,th}^{\mathrm{Hyd}}$	-	Number of hydrogenation equipment at capacity level *th* in region *j*
$N_{j,tl}^{\mathrm{Liq}}$	-	Number of liquefaction equipment at capacity level *tl* in region *j*
$N_{j,k,c,d}^{\mathrm{Pipe}}$	-	Number of pipelines with diameter *dp* transporting hydrogen in form *c* from region *j* to region *k*
$N_{j,c}^{\mathrm{RF}}$	-	Number of refuelling station receiving hydrogen in form *c* in region *j*

$N_{j,k,c}^{\text{Trip}}$	-	Number of trips required to transport hydrogen in form *c* from region *j* to region *k* using truck
$N_{j,k,c}^{\text{Truck}}$	-	Number of truck required to transport hydrogen in form *c* from region *j* to region *k*
p	-	Phase of tilt angle adjustment
p_m	-	Start day for month *m*
p_p	-	Start day of phase *p*
P^{Cons}	-	Unit power consumption for hydrogen compression
P^{rate}	-	Penetration rate of HESC network
$PEWP$	-	Potential energy waste possibility
$\text{Petrol}^{\text{cost}}$	-	Petrol cost
$Pipe^{\text{cost}}$	-	Pipeline annual cost
$Pipe_{j,k,c,dp}^{\text{range}}$	-	Throughput of pipe with diameter *dp* transporting hydrogen in form *c* from region *j* to region *k*
$\text{Pipe}_{dp}^{\text{range,UL}}$	-	Maximum allowable throughput of pipe with diameter *dp*
$\text{Pipe}_{dp}^{\text{ucapex}}$	-	Unit capital cost of pipeline with diameter *dp*
$\text{Pipe}_{dp}^{\text{uopex}}$	-	Unit operating cost of pipeline with diameter *dp*
Pop_j	-	Population in region *j*
$\text{Pop}^{\text{Total}}$	-	Total population in all study regions
$\text{PR}_c^{\text{Losses}}$	-	Hydrogen losses when being processed to convert into form *c*
PRV^{FE}	-	Fuel economy of petrol vehicle
PV^{cap}	-	Solar panel capacity
PV_j^{Cap}	-	Capacity of solar panel at region *j*
PV^{cost}	-	Solar panel annual cost
PV^{Eff}	-	Solar panel efficiency
$\text{PV}^{\text{ucapex}}$	-	Solar panel unit capital cost
PV^{uopex}	-	Solar panel unit operating cost
q_m	-	End day for month *m*
q_p	-	End day of phase *p*
RF^{cost}	-	Refuelling station annual cost
$\text{RF}_c^{\text{Losses}}$	-	Losses of hydrogen form *c* during unloading and handling at refuelling station

$\mathrm{RF}_{c}^{\mathrm{ucapex}}$	-	Refuelling station unit capital cost
$\mathrm{RF}_{c}^{\mathrm{UL}}$	-	Maximum capacity of refuelling station receiving hydrogen in form *c*
$\mathrm{RF}_{c}^{\mathrm{uopex}}$	-	Refuelling station unit operating cost
SH_{j}	-	Average daily sun hours in region *j*
SOC_{t}^{Bat}	-	State of charge of battery at time *t*
$\mathrm{SOC}^{\mathrm{Bat,max}}$	-	Maximum energy storage capacity of battery
$SOC^{\mathrm{Bat,min}}$	-	Minimum state of charge of battery
SOC_{t}^{HS}	-	Level of hydrogen tank at time *t*
$SOC^{\mathrm{HS,max}}$	-	Maximum storage level of hydrogen tank
$SOC^{\mathrm{HS,min}}$	-	Minimum storage level of hydrogen tank
$\mathrm{SR}_{d,t}$	-	Solar irradiation on day *d* and time *t*
SR_{j}	-	Solar irradiance at region *j*
SR_{t}	-	Solar irradiation at time *t*
$\mathrm{ST}_{d,t}$	-	Solar time
ST^{cost}	-	Solar tracker annual cost
$\mathrm{ST}^{\mathrm{ucapex}}$	-	Solar tracker unit capital cost
$\mathrm{ST}^{\mathrm{uopex}}$	-	Solar tracker unit operating cost
t	-	Time (hour) in a day
tc	-	Set of compressors with capacity level *tc*
th	-	Set of hydrogenation units with capacity level *th*
tl	-	Set of liquefaction units with capacity level *tl*
$\mathrm{T}_{j,k,c}^{\mathrm{Trip}}$	-	Time required to transport hydrogen form c from region *j* to region *k* using trucks
TA	-	Operation time of truck in a day
TC_{c}	-	Unit capacity of truck carrying hydrogen in form *c*
$\mathrm{TotalCost}^{\mathrm{Con}}$	-	Total cost of conventional energy use
$TotalCost^{\mathrm{HESC}}$	-	Total cost of HESC in a year
$Truck^{\mathrm{cost}}$	-	Truck transportation annual cost
$\mathrm{Truck}^{\mathrm{FE}}$	-	Maximum state of charge of battery
$\mathrm{Truck}_{c}^{\mathrm{ucapex}}$	-	Minimum state of charge of battery
$\mathrm{Truck}_{c}^{\mathrm{uopex}}$	-	Maximum storage level of hydrogen tank
TS	-	Minimum storage level of hydrogen tank

TZ	-	Hydrogen inventory at time t
VH^{Total}	-	Solar irradiance at time t
Y^{BAT}	-	Solar time
Y^{COMP}	-	Solar tracker unit capital cost
Y^{CONV}	-	Solar tracker unit operating cost
Y^{EL}	-	Time period
Y^{INV}	-	Time required to transport hydrogen form c from region j to region k using truck
Y^{FC}	-	Operation time of truck in a day
Y^{RF}	-	Unit capacity of truck carrying hydrogen in form c
Y^{SL}	-	Annualized capital cost of HESC
Y^{Truck}	-	Annual operating cost of HESC
$Truck^{FE}$	-	Fuel economy of truck
$Truck_c^{ucapex}$	-	Truck unit capital cost
$Truck_c^{uopex}$	-	Truck unit operating cost
TS	-	Average speed of truck
TZ	-	Time zone
VH^{Total}	-	Total number of vehicles in study regions
Y^{BAT}	-	Battery lifespan
Y^{COMP}	-	Compressor lifespan
Y^{CONV}	-	Converter lifespan
Y^{EL}	-	Electrolyzer lifespan
Y^{INV}	-	Inverter lifespan
Y^{FC}	-	Fuel cell lifespan
Y^{RF}	-	Refuelling station lifespan
Y^{SL}	-	System lifespan
Y^{Truck}	-	Truck lifespan

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

The concerns on energy security and climate change have been the driving force for the exploration of sustainable energy supply. Hydrogen is a promising energy carrier that can be generated from renewable energy sources and has no carbon emission at the point of use. This chapter provides the research background of the study, as well as the problem statement, research goals, scopes and contributions of this thesis.

1.2 Research Background

The rapid economic growth in the world is inextricably linked with elevated energy use, resulting in increased global energy demand and pressure on the energy supply (Sáez-Martínez et al., 2016). As one of the fastest developing ASEAN countries, Malaysia has a gross domestic product (GDP) growth of 4.3% in 2019, with a GDP of 11,091 USD per capita (FocusEconomics, 2021). In 2020, about 4.11 EJ of primary energy is consumed in Malaysia with over 94% of energy produced from fossil fuels. Figure 1.1 shows the primary energy consumption by fuel type in Malaysia, where the heavy reliance on fossil fuels would result in 256 MT of carbon dioxide emissions if no mitigation measure is applied (BP, 2021). As illustrated in Figure 1.2, the national energy demand has been increasing over the years and transport sector contributes to significant energy use, which is about 36% of total energy demand in 2018 (Energy Commission, 2021).

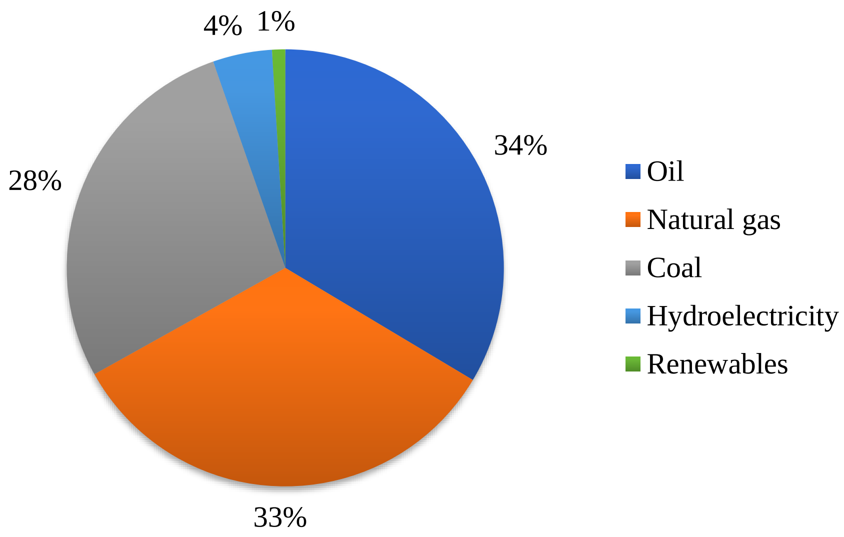

Figure 1.1 Primary energy consumed by fuel type in Malaysia (BP, 2021)

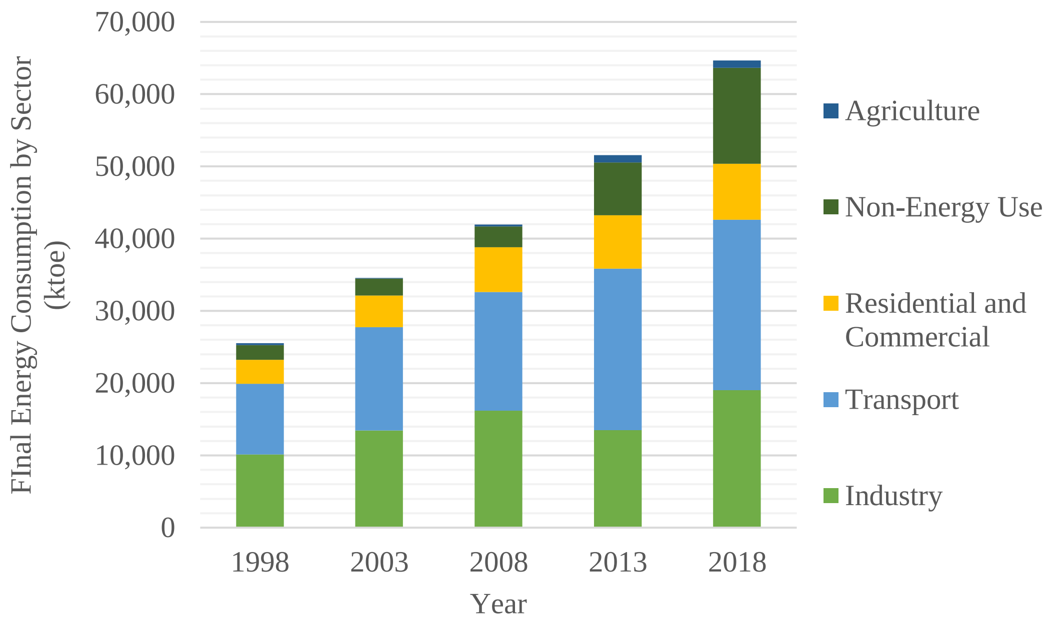

Figure 1.2 Final energy demand by sector in Malaysia (Energy Commission, 2021)

Excessive consumption of fossil fuels has risked energy security globally. Figure 1.3 shows the reserve-to-production (R/P) ratios of the conventional fuels, which represent the duration that a fuel reserve could last if being used at the same rate as in 2020. Based on the findings, global oil and gas reserves would exhaust within 55 years, while the fossil fuel reserves in Malaysia would be used up in 13 years (BP, 2021).

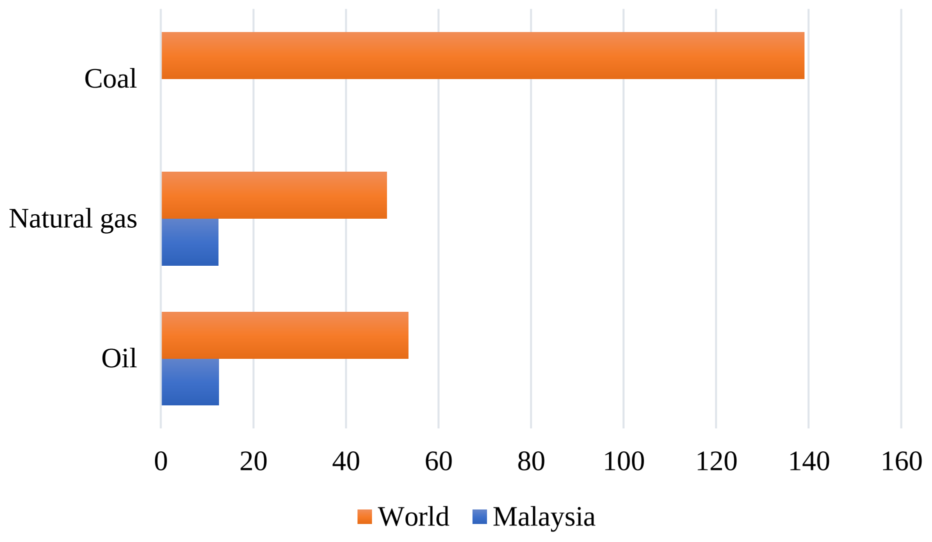

Figure 1.3 Reserve-to-production (R/P) ratio of fossil fuels reserves in Malaysia and the world (BP, 2021)

Meanwhile, the utilization of fossil fuels causes greenhouse gases (GHG) emissions which eventually leads to global warming. GHG released in a business-as-usual scenario could heat up the planet by 4°C, which results in the shift of climate zones and rise of sea level (Hydrogen Council, 2017). The significance of this issue can be seen through Paris Agreement 2015, where 195 countries pledged to keep the rise of global average temperature to well below 2°C while attempting to restrict the warming to 1.5°C above pre-industrial levels. As one of the participating countries, Malaysia has committed to reducing the GHG emissions of GDP by 45% in 2030 in relative to 2005 (Lian, 2018).

1.2.1 GHG Mitigation Actions and Policies in Malaysia

In Malaysia's Third Biennial Update Report (BUR3) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), the anthropogenic emissions and removals of GHG in four sectors are being assessed: (i) energy, (ii) industrial processes and product use (IPPU), (iii) agriculture, forestry and other land use (AFOLU), and (iv) waste. As displayed in Figure 1.4, energy sector gives the highest GHG emission in Malaysia, while the land use, land-use change and forestry (LULUCF) sector contributes to a significant GHG removal. Activities in LULUCF sector could offset the GHG emissions either by increasing the removals of GHG from atmosphere through tree plantation and forest management, or by reducing emissions with curbed deforestation (UNFCCC, 2021). Nevertheless, with the stabilized LULUCF's sink capacity, the mitigation of significant GHG emissions in energy sector is crucial to further reduce the overall emissions. In 2016, the increased emissions from LULUCF activities are caused by infrastructure development such as the construction of highways and new airports (MEWA, 2020).

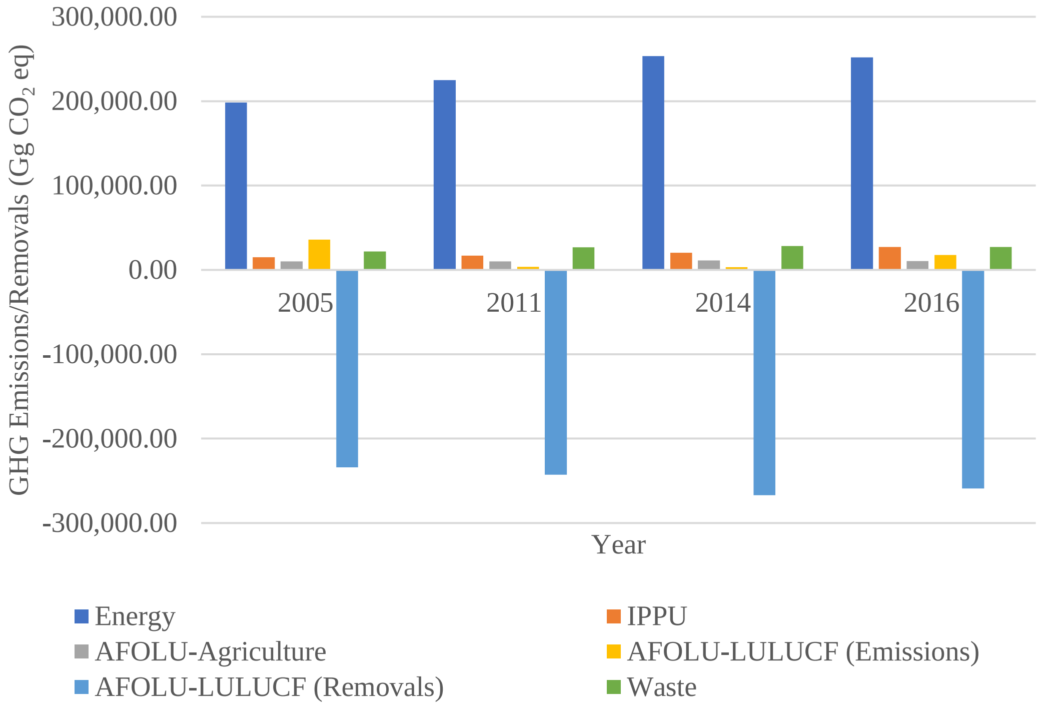

Figure 1.4 GHG inventory by sector in Malaysia (MEWA, 2020)

Table 1.1 displays the key mitigation actions implemented by Malaysia to reduce GHG emissions and their effectiveness in emission avoidance. Generally, forestry sector has mitigated the greatest amount of GHG emissions by being a net sink, followed by the generation of electricity through hydropower, recycling of wasted paper, and the recovery of biogas from palm oil mill effluent (POME).

Table 1.1 Key mitigation actions and emissions avoidance achieved in 2016 (MEWA, 2020)

Sector	Sub-sector	Mitigation Actions	Relevant Policy/Information	Avoided emissions (Gg CO_2 eq.)	Share (%)
Energy	Renewable Energy	Feed-in-Tariff (FiT)	• National Renewable Energy Policy and Action Plan 2010 highlights the need of an implementing agency for the implementation, management, and administration of Feed-in-Tariff (FiT) and related Renewable Energy Fund (REF) mechanism. • Renewable Energy Act 2011 establishes FiT and REF mechanisms • SEDA is formed as a statutory body under Sustainable Energy Development Authority Act 2011 to manage and administer the implementation of the FiT initiatives	460.52	1.3
		Hydropower	Share of hydropower in electricity generation mix increased from 5.35% (6,361 GWh) in 2010 to 12.83% (20,357 GWh) in 2016	6,570.15	18.3
		Other renewable energy by public and private licensees	Renewable electricity generation by public and private licensees beyond the FiT scheme	231.92	0.6
	Energy Efficiency	National Energy Efficiency Action Plan	Introduced in 2016 to promote energy efficiency in residential, commercial and industrial sectors through five key initiatives: : (i) promotion of 5-Star Rated Appliances, (ii) Minimum Energy Performance Standards, (iii) Energy Audits and Energy Management in Buildings and Industries, (iv) promotion of co-generation, and (v) Energy Efficient Building Design	458.02	1.3

Table 1.1 Key mitigation actions and emissions avoidance achieved in 2016 (MEWA, 2020) (cont)

Sector	Sub-sector	Mitigation Actions	Relevant Policy/Information	Avoided emissions (Gg CO_2 eq.)	Share (%)
Energy	Transportation	Rail based public transport	National Land Public Transport Master Plan targets 40% modal share of public transport in urban areas by 2030	212.93	0.6
		Use of energy-efficient vehicles	Tax incentives for hybrid and electric vehicles	90.65	0.3
		Use of palm-based biodiesel in blended petroleum diesel	National Biofuel Policy 2006 and Malaysian Biofuel Industry Act in 2007 were launched to enforce the blend of palm-based biodiesel with petroleum diesel	1,127.34	3.1
		Use of natural gas in vehicles	• Natural Gas for Vehicles programme was launched in late 1990s in order to promote the use of natural gas vehicles in public transport sector • Retail price of natural gas for vehicle fuel is set at half the retail price of petrol. Also, tax exemption or reduction were given to natural gas vehicles and the related equipment.	114.77	0.3
Waste	Paper recycling		• The National Solid Waste Management Policy 2006 and the Eleventh Malaysia Plan aims for 22% recycling in 2020. • The revised National Solid Waste Management Policy 2016 targets a 40% waste valorization in total, 22% to be achieved through recycling and 18% through waste treatment.	3,937.76	11.0

Table 1.1 Key mitigation actions and emissions avoidance achieved in 2016 (MEWA, 2020) (cont)

Sector	**Sub-sector**	**Mitigation Actions**	**Relevant Policy/Information**	**Avoided emissions (Gg CO_2 eq.)**	**Share (%)**
Waste	Biogas recovery from palm oil mill effluent		• Encouraged in fifth core Entry Point Project in Palm Oil National Key Economic Areas programme • From 1st January 2014 onwards, all new mills or existing mills applying for expansion must install biogas trapping or methane avoidance facilities.	2,377.84	6.6
Forestry	Reducing deforestation, Sustainable management of forest and Conservation of carbon stocks		• Malaysian Timber Certification Scheme was launched in 2001 to ensure sustainable timber harvesting • The annual allowable cut in the Permanent Reserved Forest is capped at 85 m^3/ha for each Malaysia Plan period • A target is set to increase the Protected Area to at least 20% by 2025	20,307.50	56.6
			Total	**35,889.40**	**100.0**

Apart from the mitigation actions outlined in Table 1.1, some financial incentives were also introduced by the government to facilitate the growth of green energy. These include the Green Technology Financing Scheme which was first proposed in 2010 to support the development of green technology in Malaysia. The Green Technology Financing Scheme 2.0 approved in 2019 provides easier access to funding with 2% rebate on interest or profit per annum and 60% government guarantee of green component cost (MGTC, 2021b). Moreover, Green Investment Tax Allowance and Green Income Tax Exemption were also introduced as tax incentives. Green Investment Tax Allowance is applicable for green assets or projects, while Green Income Tax Exemption is applicable for green service providers (MGTC, 2021a). Besides, the Green Technology Master Plan Malaysia 2017-2030 creates a framework to facilitate the mainstreaming of green technology in energy, manufacturing, transportation, building, waste and water sectors (KeTTHA, 2017).

1.2.2 Hydrogen-based Energy System and its Development in Malaysia

As described in Section 1.2.1, the decarbonization of energy sector is crucial to reduce GHG emissions in Malaysia. To achieve this, the use of renewable energy and low-carbon fuel should be further promoted. Being an energy carrier with high heating value and clean emission (Acar and Dincer, 2018), hydrogen could play a major role in future energy system to complement the intermittent renewable energy. It can be used as a long-term energy storage to store renewable energy in large scale, and the stored energy can be released through combustion or electrochemical conversion (Martin et al., 2020). Moreover, hydrogen can also be used as fuel for transportation or heating (Hydrogen Council, 2017). A hydrogen-based energy system can be either single-site or multi-site: single-site system considers the energy supply and demand for one location, while multi-site energy system considers the supply-demand balance across multiple locations.

As hydrogen only emits water at the point of use, synthesizing hydrogen from renewable energy sources would make the entire energy system clean and sustainable. While fossil fuels have been dominating global hydrogen production, IEA (2019) reported that the declining costs in solar photovoltaic (PV) and wind electricity have grown the interest in electrolytic hydrogen, and there have been several demonstration projects in recent years. Table 1.2 lists the recent hydrogen projects reported around the world, where the production of electrolytric hydrogen is powered by solar or wind energy. With strategic geographical location, Malaysia receives abundant solar radiation throughout the year with most places having daily solar radiation mean of 4.7 - 6.5 kWh/m^2 (Petinrin and Shaaban, 2015). Malaysia plays a vital role in solar power industry and is currently the third major producer of solar PV cells and modules in the world. Based on Malaysian Solar PV Roadmap 2017, Malaysia will be a hub for solar cell manufacturing by 2030 (Vaka et al., 2020). Hence, the potential to produce solar-based electrolytic hydrogen is worth investigating in Malaysian context.

Table 1.2 Recent hydrogen projects reported around the world

Location	**Energy Source**	**Production Technology**	**Project Status**	**Reference**
Fukushima, Japan	Solar (20 MW)	Electrolysis	Completed	(Rod, 2020)
Ningxia, China	Solar (200 MW)	Electrolysis	Under construction	(Jennifer, 2020)
Dongara, Austrialia	Solar and wind	Electrolysis (1000 MW)	Under construction	(Marija, 2020)
Laage, Germany	Solar	Electrolysis (24 MW)	Under construction, expected to be launched by 2022	(Joanna, 2021)

Since 8th Malaysia plan, Malaysia government has made hydrogen fuel cells as priority research for development. This is evidenced by the hydrogen roadmap proposed during that period, as shown in Figure 1.5. Nevertheless, most of the targets have not been achieved up to date. Daud et al. (2017) stated the greatest obstacle for Malaysia on the road towards hydrogen economy is the development of large-scale supportive infrastructure in production, conversion, and storage technologies that cater for hydrogen energy applications.

In recent years, Sarawak authorities have poured more efforts into the development of hydrogen economy. In 2019, Sarawak Energy has commissioned an integrated hydrogen production plant and refueling station in collaboration with Linde, which allows the fueling up 5 fuel cell buses and 10 fuel cell cars per day (Sarawak Energy, 2020). In addition, Sarawak Energy has signed a memorandum of understanding with Petronas in 2020 to collaborate on green hydrogen commercial production and its value supply chain in Asia (Sampson, 2020). While Petronas has been producing blue hydrogen as a by-product of liquefied natural gas production, they are now looking into the commercial production of green hydrogen (Forbes, 2021).

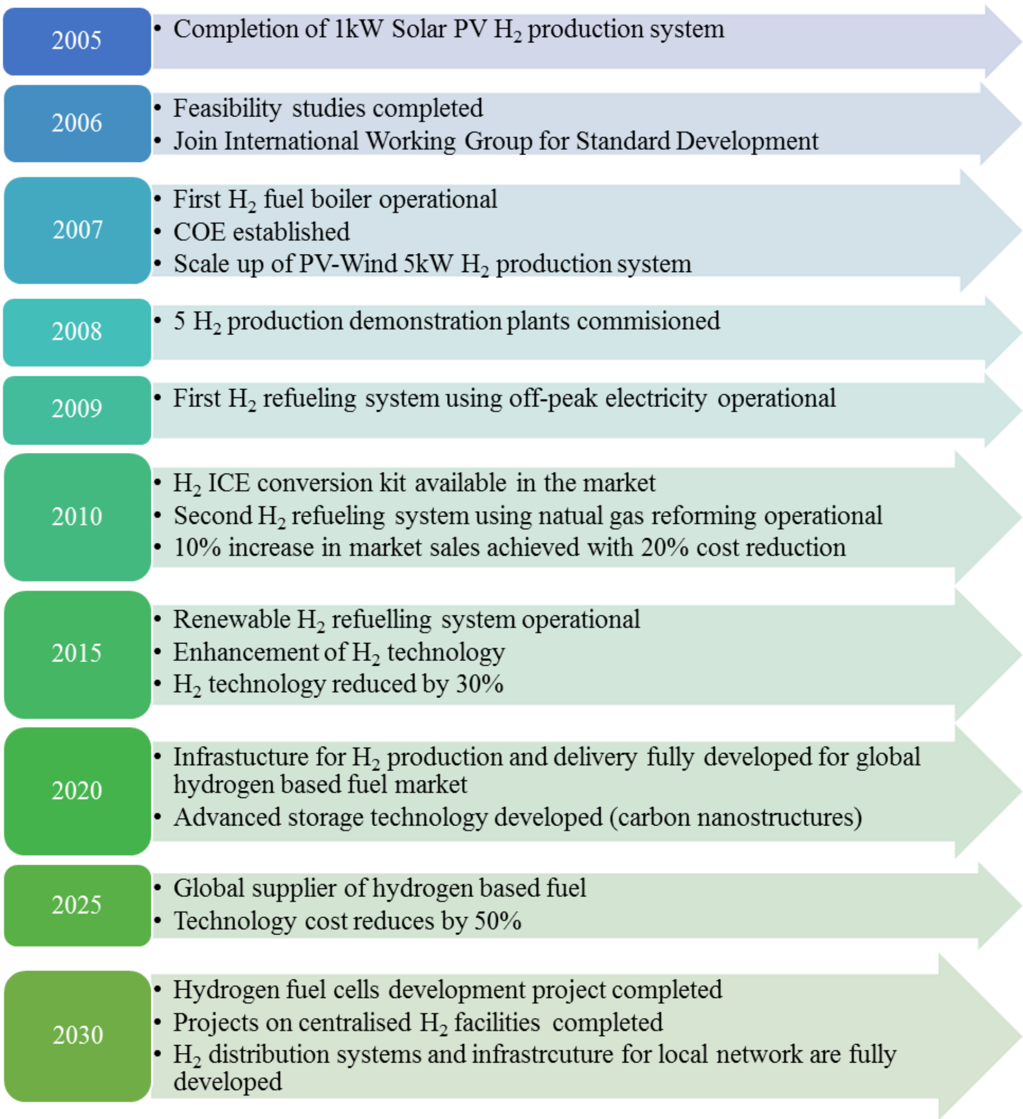

Figure 1.5 Hydrogen roadmap in Malaysia (Daud et al., 2017)

1.3 Problem Statement

Although hydrogen is perceived to be the fuel of the future, there are a lot of challenges to be overcome before it can play its role adequately. First of all, the development of hydrogen infrastructure should be carefully planned for a successful implementation of hydrogen economy. This requires the optimization of hydrogen production, conversion, storage, and transportation facilities or in other words, the hydrogen supply chain (HSC). For the planning of HSC, spatial conditions are important factors to be considered to determine the suitable locations for the installation of supply chain infrastructures.

While the optimization of HSC has been extensively studied in many countries, the investigation in Malaysian context is still lacking. Moreover, most of the available HSC studies only focused on limited hydrogen applications. For instance, some studies targeted hydrogen as vehicle fuel by delivering the end-product to refuelling stations, while others proposed the use of hydrogen as electrical energy storage for intermittent energy sources. In such cases, the possible integration of both systems, as well as the interconvertibility of hydrogen and electricity are not being assessed. Targeting the use of hydrogen as vehicle fuel, energy storage, and secondary electricity supply in a single model could integrate the hydrogen and electricity supply systems for more comprehensive planning.

To address the identified research gaps, this study intends to develop a holistic framework to determine the optimal solution for the implementation of hydrogen economy. Considering the solar energy potential in Malaysia and the growing interest on electrolytic hydrogen, the production of hydrogen from solar PV via water electrolysis will be focused in this study. The developed framework will be used to optimize the hydrogen-electricity supply system (HESS) at micro and macro levels. Micro-planning of HESS involves the optimization of a single-site microgrid that produces hydrogen and electricity for energy demands. Meanwhile, the optimization of HESS at macro-level provides a bigger picture by designing the HESS at regional, state or country level, considering a multi-site operation. Geographical constraints will be applied to decide suitable locations for the placement of supply chain infrastructures.

1.4 Research Objective

This research aims to develop a systematic framework for the optimization of an integrated hydrogen-electricity supply system. Mathematical models are developed to optimize the hydrogen-electricity supply system at micro and macro levels:

1. To optimize the orientation of solar panel through mathematical modelling considering manual tilt angle adjustment and solar tracker installation for maximum solar radiation yield in a photovoltaic system.
2. To optimize the design and operation of single-site hydrogen-electricity supply system that caters for fuel and electricity demands.
3. To optimize the siting and capacities of supply chain infrastructures in a multi-site hydrogen-electricity supply chain.

1.5 Scope of Work

To achieve the intended objectives, the scope of work has been detailed as follows:

1. Conducting literature review and analyzing the state-of-art practice on:

    a) Solar PV and solar tracking system

    b) Microgrid and its components (inverter, battery, hydrogen storage, electrolyzer, fuel cell, energy management strategy)

    c) Hydrogen supply chain (resources, production methods, conversion technologies, storage and transportation modes, end-uses).

    d) Mathematical optimization of hydrogen -based microgrid and hydrogen supply chain.

2. Formulating a mathematical model for solar radiation modelling. The mixed-integer nonlinear programming model is programmed in MATLAB to determine the optimal orientation of solar panel that gives maximum solar radiation yield. The scope of model is limited to the optimization of solar panel orientation through manual tilt angle adjustment and solar tracking systems, which is demonstrated and validated using a case study in Johor Bahru.

3. Developing mathematical models for the optimization of single-site hydrogen-electricity supply system that caters for transportation fuel and electricity demands. The specific scope includes:

    a) Developing a linear programming model that optimizes hydrogen-electricity supply system based on the hourly energy generation and load profiles in a day. The developed model is programmed in General Algebraic Modelling Systems (GAMS) and demonstrated through a case study with 24 hours energy profiles in a day.

    b) Extending the mathematical model developed in (a) to consider the daily and seasonal variations of energy supply and demand profiles. Hierarchical energy management strategies are being introduced to regulate microgrid actions based on the available energy supply and level of energy storage. The nonlinear programming model is programmed in MATLAB and demonstrated through a case study with 8760 hours energy profiles in a year.

    c) Performing scenario analysis to evaluate the cost-effectiveness of solar tracking system in the proposed energy system.

    d) Performing sensitivity analysis to determine the sensitivity of optimal solution towards changes in microgrid component costs.

4. Developing a geographically explicit optimization model for multi-site hydrogen-electricity supply chain to fulfill the daily transportation fuel and electricity demands. The specific scope includes:

a) Performing spatial data processing and site suitability analysis using ArcGIS. The spatial analysis methodology is demonstrated using Johor as the case study location.

b) Developing a mathematical model for the optimization of hydrogen-electricity supply chain considering the production, conversion, storage, and transportation of hydrogen and electricity. The spatial data obtained in (a) is used as the input for the mathematical model. The mixed-integer linear programming model is programmed in GAMS to determine the optimal solution.

c) Performing sensitivity analysis to determine the sensitivity of optimal solution towards changes in supply chain component costs.

1.6 Research Contributions

The key contributions of this research work are outlined below:

1. A new mathematical optimization model for single-site hydrogen-electricity supply system has been developed. This allows the concurrent targeting of hydrogen and electrical loads during the design of microgrid, and the interconversion between electricity and hydrogen can be modelled. In addition, the fluctuations in intermittent energy sources and load demands are considered for a robust design of microgrid.

2. A new geographically explicit optimization model for hydrogen-electricity supply chain has been developed. This model allows strategic planning of locations and capacities of supply chain infrastructures including the production, conversion, storage and transportation facilities. The integration between hydrogen and electricity supply network is considered and the optimized network will satisfy both transportation fuel and electricity requirements of the study locations.

3. The optimization models developed will contribute to the field of Process System Engineering (PSE) for designing and optimizing the hydrogen-electricity supply system.

4. With Malaysia data being used in case studies, the results reflect the feasibility of implementing hydrogen energy system in Malaysia.

Publications produced from this research work can be found in the List of Publications.

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LIST OF PUBLICATIONS

Journals with Impact Factor

1. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H., Hashim, H., Ling, G.H.T., Ho, C.S. and Ab Muis, Z., 2021. Optimization of a Standalone Photovoltaic-Based Microgrid with Electricity and Hydrogen Loads. *Energy*, p.121218. **(Q1, IF 7.147)**
2. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H., Hashim, H., Ling, G.H.T., Ho, C.S. and Ab Muis, Z., 2021. Optimization of Photovoltaic-Based Microgrid with Hybrid Energy Storage: A P-graph Approach. *Energy*, p.121088. **(Q1, IF 7.147)**
3. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H., Hashim, H., Liew, P.Y. and Ab Muis, Z., 2021. Targeting and scheduling of standalone renewable energy system with liquid organic hydrogen carrier as energy storage. *Energy*, *218*, p.119475. **(Q1, IF 7.147)**
4. **Mah, A.X.Y.**, Ho, W.S., Bong, C.P.C., Hassim, M.H., Liew, P.Y., Asli, U.A., Kamaruddin, M.J. and Chemmangattuvalappil, N.G., 2019. Review of hydrogen economy in Malaysia and its way forward. *International Journal of Hydrogen Energy*, 44(12), pp.5661-5675. **(Q2, IF 5.816)**

Indexed Conference Proceedings

1. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H. and Hashim, H., 2021. Optimization of Photovoltaic Array Orientation and Performance Evaluation of Solar Tracking Systems. *Chemical Engineering Transactions*, *83*, pp.109-114. **(SCOPUS)**
2. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H. and Hashim, H., 2021. Economic Assessment of Photovoltaic-Based Microgrid Incorporated with Solar Tracking System. *Chemical Engineering Transactions*, *83*, pp.451-456. **(SCOPUS)**
3. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H. and Hashim, H., 2020. Spatial Planning of Photovoltaic-Based Hydrogen Supply Chain: Optimal Site Location and Supply Chain Operation. *Chemical Engineering Transactions*, *81*, pp.613-618. **(SCOPUS)**
4. **Mah, A.X.Y.**, Ho, W.S., Hassim, M.H., Hashim, H., Liew, P.Y., Asli, U.A., Muis, Z.A. and Ling, G.H.T., 2020. Optimization of Hydrogen Supply Chain: A Case Study in Malaysia. *Chemical Engineering Transactions*, *78*, pp.85-90. **(SCOPUS)**