Supplementary Material

This document introduces the values of input parameters used in the optimizations of the IPA of Singapore. Table A.1 reports the energy and economic characteristics of the port yard tractors and tugboats fleets. Table A.2 reports the energy and economic characteristics of the HRS chosen to refuel the port yard tractors and tugboats fleets. Table A.3 reports the cost, performance and carbon impact of each energy system unit, related to the current energy and market scenario.

Table A.1 Energy and economic characteristics of the port yard tractors and tugboats fleets [1–6].

	Unit	**Yard tractor**	**Tugboat**
Number of vehicles	-	160	6
Diesel demand	kg_{oil}/day	124	2357
H_2 demand	kgH_2/day	21	400
Cost of hybrid H_2 sol.	M€/unit	162	1000
Lifetime of hybrid H_2 sol.	year	25	25
O&M cost of hybrid H_2 sol.	%	5	5

Table A.2 Energy and economic characteristics of the HRS chosen to refuel the port yard tractors and tugboats fleets [7–9].

	Unit	**Yard tractor**	**Tugboat**
Number of HRS	-	6	2
Peak hourly capacity	kgH_2/h	100	200
Daily capacity	kgH_2/day	600	1200
Cost	M€	2.5	5
O&M cost	%	5	5
Lifetime	year	25	25

Table A.3 Value of the model input parameters. Parameters are related to the costs, performances and carbon impact of the energy conversion and storage units, and energy flows entering and outgoing from the energy system.

Photovoltaic plant				
	Description	**Unit**	**Value**	**Refs.**
$A_{PV,max}$	Max available area for PV installation	km^2	0.24	Assumed
c_{pv}	Cost of PV	€/kW_P	840	[10–12]
$c_{pv_{O\&M}}$	O&M cost of PV	%	1	[10,13–15]
η_{PV}	PV efficiency	%	18	Assumed
LT_{PV}	Lifetime of the PV plant	year	15	[10,13–15]
Lithium-ion battery				
c_{batt}	Cost of battery	€/kWh	380	[11,16]
$c_{batt_{O\&M}}$	O&M cost of battery	%	1	[17–21]
η_{batt}	Battery efficiency	%	90	[17–21]
$k_{max,batt}$	Max batt capacity	-	0.9	Assumed
$k_{min,batt}$	Min batt capacity	-	0.2	Assumed
LT_{batt}	Lifetime of battery	year	15	[17–21]
Alkaline electrolyzer				
C_{elect}	Cost of AEL (BoP + stack)	€/kW_{el}	2500	[22–24]
$c_{elect_{O\&M}}$	O&M cost of AEL	%	2	[22–24]
$C_{elect_{stack}}$	Cost of AEL stack	€/kW_{el}	1600	[22–24]
$D_{min_{elect}}$	Min size of AEL	kW_{el}	1000	[22–24]

$k_{1_{elect}}$	AEL proportionality coefficient	kg/kWh	0.0074	[22–24]
$k_{2_{elect}}$	AEL proportionality coefficient	kg/kWh	0.0063	[22–24]
$k_{3_{elect}}$	AEL proportionality coefficient	-	0.3	[22–24]
$k_{max,elect}$	Max power load of AEL	-	1	[23,25]
$k_{min,elect}$	Min power load of AEL	-	0.2	[23,25]
LT_{elect}	Lifetime of AEL BoP	year	20	[25,26,35–43,27–34]
$LT_{elect_{stack}}$	Lifetime of AEL stack	year	10	[25,26,35–43,27–34]
Hydrogen compressors				
$c_{comp_{O\&M}}$	O&M cost of LP and HP compressor	%	8	[13,15,44]
$c_{comp_{HP}}$	Cost of HP compressor	€/kW$_{el}$	7000	[45,46]
$c_{comp_{LP}}$	Cost of LP compressor	€/kW	6000	[45,46]
eta_{el}	Electric motor efficiency	-	0.96	Assumed
eta_{is}	Isentropic efficiency	-	0.8	Assumed
eta_{mech}	Mechanical efficiency	-	0.98	Assumed
$k_{1_{comp_{LP}}}$	Proportionality coefficient of LP compressor	kWh/kg	1.77	[45,46]
$k_{1_{comp_{HP}}}$	Proportionality coefficient of HP compressor	kWh/kg	0.61	[45,46]
$k_{2_{comp_{LP}}}$	Proportionality coefficient of LP compressor	-	2.3238	[45,46]
$k_{2_{comp_{HP}}}$	Proportionality coefficient of HP compressor	-	0.67	[45,46]
$k_{max,comp}$	Max power load of PEME	-	1	Assumed
$k_{min,comp}$	Min power load of PEME	-	0.2	Assumed
$LT_{comp_{LP}}$	Lifetime of LP compressor	year	10	[13,15,44]

$LT_{comp_{HP}}$	Lifetime of HP compressor	year	10	[13,15,44]
Compressed hydrogen storages				
$c_{HS_{LP}}$	Cost of LP H_2 storage	€/kgH_2	1000	[22,23,47]
$c_{HS_{HP}}$	Cost of HP H_2 storage	€/kgH_2	1500	[22,23,47]
$c_{HS_{O\&M}}$	O&M cost of LP and HP H_2 storages	%	2	[21,48–52]
$D_{min_{HS}}$	Min size of H_2 storage	kg	100	Assumed
$k_{max,HS}$	Max H_2 storage capacity	-	0.8	Assumed
$k_{min,HS}$	Min H_2 storage capacity	-	0.2	Assumed
$LT_{HS_{LP}}$	Lifetime of LP H_2 storage	year	25	[21,48–52]
$LT_{HS_{HP}}$	Lifetime of HP H_2 storage	year	25	[21,48–52]
High-Temperature PEMFC				
c_{FC}	Cost of FC (BoP + stack)	€/kW_{el}	4000	[24,53–56]
$c_{FC_{stack}}$	Cost of FC stack	€/kW_{el}	2500	[24,53–56]
$c_{FC_{O\&M}}$	O&M cost of FC	%	1	[24,53–56]
$D_{min_{FC}}$	Min size of FC	kW_{el}	100	[24,53–56]
$k_{1_{FC}}$	Proportionality coefficient of FC	kg/kWh	2.59	[24,53,56]
$k_{2_{FC}}$	Proportionality coefficient of FC	-	-0.38	[24,53,56]
$k_{3_{FC}}$	Proportionality coefficient of FC	-	0.78	[24,53,56]
$k_{4_{FC}}$	Proportionality coefficient of FC	-	-0.11	[24,53,56]
$k_{max,FC}$	Max power load of FC	-	1	Assumed
$k_{min,FC}$	Min power load of FC	-	0.3	Assumed

LT_{FC}	Lifetime of FC BoP	year	20	[24,53–56]
$LT_{FC_{stack}}$	Lifetime of FC stack	year	10	[24,53–56]
Refrigerator of the hydrogen refuelling station				
c_{refr}	Cost of refrigerator	€/kW$_{el}$	5374	[13,15]
$c_{refr_{O\&M}}$	O&M cost of refrigerator	%	1	[13,15]
LT_{refr}	Lifetime of refrigerator	year	15	Assumed
Thermal energy storage				
c_{TES}	Cost of thermal energy storage	€/kWh	30.21	[12,16]
$c_{TES_{O\&M}}$	O&M cost of thermal energy storage	%	1	[12,16]
$k_{1_{TES}}$	Proportionality coefficient of thermal energy storage	-	0.95	[12,16]
$k_{max,TES}$	Max power load of thermal energy storage	-	1	[12,16]
$k_{min,TES}$	Min power load of thermal energy storage	-	0.3	[12,16]
LT_{TES}	Lifetime of thermal energy storage	year	20	[12,16]
Vapour compression chiller				
c_{VCC}	Cost of vapour compressor chiller	€/kW$_{el}$	142	[12,16,57]
$c_{VCC_{O\&M}}$	O&M cost of vapour compressor chiller	%	2	[12,16,57]
$D_{min_{VCC}}$	Min size of vapour compressor chiller	kW$_{el}$	100	[12,16,57]
$k_{1_{VCC}}$	Proportionality coefficient of vapour compressor chiller	-	7.052876	[12,16,57]
$k_{2_{VCC}}$	Proportionality coefficient of vapour compressor chiller	kW$_{el}$	-0.64651	[12,16,57]
$k_{max,VCC}$	Max power load of vapour compressor chiller	-	1	[12,16,57]
$k_{min,VCC}$	Min power load of vapour compressor chiller	-	0.12	[12,16,57]

LT_{VCC}	Lifetime of vapour compressor chiller	year	25	[12,16,57]
Absorption chiller				
c_{ABC}	Cost of ABC	€/kW_{th}	220	[12,16,57]
$c_{ABC_{O\&M}}$	O&M cost of the ABC	%	2	[12,16,57]
$D_{min_{ABC}}$	Min size of the ABC	kW_{th}	100	[12,16,57]
$k_{1_{ABC}}$	Proportionality coefficient of the ABC	-	1.7153	[12,16,57]
$k_{2_{ABC}}$	Proportionality coefficient of the ABC	kW_{th}	-0.0462	[12,16,57]
$k_{max,ABC}$	Max power load of the ABC	-	1	[12,16,57]
$k_{min,ABC}$	Min power load of the ABC	-	0.17	[12,16,57]
LT_{ABC}	Lifetime of the ABC	year	25	[12,16,57]
Electric power grid				
c_{el}^{-}	Price of power sold	€/kWh	0.03408	[58]
c_{el}^{+}	Price of power purchased	€/kWh	0.06958	[12]
$c_{inv_{grid}}$	Cost to increase the electric power grid capacity	€/kW_{el}/y	119.41	[59]
E_{grid}	Carbon footprint of grid electricity	kg_{CO2}/kWh	0.49	[60]
Fossil fuels				
c_{diesel}	Cost of Diesel	€/kg_{oil}	1	Assumed
E_{diesel}	Carbon footprint of Diesel	$kg_{CO2,eq}/kg_{oil}$	2.67	Assumed
c_{NG}	Cost of Natural Gas	€/kg	0.2272	Assumed
E_{NG}	Carbon footprint of natural gas	$kg_{CO2,eq}/kg_{NG}$	2.75	Assumed
Ammonia				

$c_{cracker}$	Cost of NH_3 cracker	€/kW_{el}	900	[61]
$c_{cracker_{O\&M}}$	O&M cost of NH_3 cracker	%	3	[61]
$c_{NH3_{ship}}$	Cost of NH_3 imported via ships	€/kgH_2	4.55	[23,62,63]
$c_{S_{NH3}}$	Cost of NH_3 storage	€/kgH_2	35	[64,65]
$c_{S_{NH3_{O\&M}}}$	O&M cost of NH_3 storage	%	1	[64,65]
$D_{min_{cracker}}$	Min size of NH_3 cracker	kW	1000	[61]
$E_{NH3_{ship}}$	Carbon footprint of NH_3 via ships	$kg_{CO2,eq}/kgH_2$	2.5	[66]
$k_{1_{cracker}}$	Proportionality coefficient of NH_3 cracker	-	0.76	[61]
$k_{max,cracker}$	Max power load of NH_3 cracker	-	1	[61]
$k_{min,cracker}$	Min power load of NH_3 cracker	-	0.3	[61]
$LT_{cracker}$	Lifetime of NH_3 cracker	year	25	[61]
$LT_{S_{NH3}}$	Lifetime of NH_3 storage	year	25	[64,65]

Liquified hydrogen

$c_{LH2_{ship}}$	Cost of LH_2 imported via ships	€/kgH_2	5.45	[23,62,63,67]
$c_{LH2_{vap}}$	Cost of LH_2 vaporizer	€/kW_{el}	9300	[64,65,68]
$c_{LH2_{vap_{O\&M}}}$	O&M cost of LH_2 vaporizer	%	1	[64,65,68]
$c_{S_{LH2}}$	Cost of LH_2 storage	€/kgH_2	35	[64,65]
$c_{S_{LH2_{O\&M}}}$	O&M cost of LH_2 storage	%	1	[64,65]
$D_{min_{LH2_{vap}}}$	Min size of LH_2 vaporizer	kW_{el}	100	[64,65,68]
$E_{LH2_{ship}}$	Carbon footprint of LH_2 via ships	$kg_{CO2,eq}/kgH_2$	3.1	[66,69]
$k_{1_{LH2_{vap}}}$	Proportionality coefficient of LH_2 vaporizer	-	0.90	[64,65,68]

$k_{2_{LH2_{vap}}}$	Proportionality coefficient of LH_2 vaporizer	kWh/kg	0.79	[64,65,68]
$k_{max,LH2_{vap}}$	Max power load of LH_2 vaporizer	-	1	[64,65,68]
$k_{min,LH2_{vap}}$	Min power load of LH_2 vaporizer	-	0.3	[64,65,68]
$LT_{LH2_{vap}}$	Lifetime of LH_2 vaporizer	year	25	[64,65,68]
$LT_{S_{LH2}}$	Lifetime of LH_2 storage	year	25	[64,65]
Liquid organic hydrogen carrier				
$C_{LOHC_{ship}}$	Cost of LOHC imported via ships	€/kgH_3	4.4	[23,62,63,67]
$c_{LOHC_{deh}}$	Cost of LOHC dehydrogenation unit	€/kW$_{el}$	16000	[70,71]
$c_{LOHC_{deh_{O\&M}}}$	O&M cost of LOHC dehydrogenation unit	%	3	[70,71]
$c_{S_{LOHC}}$	Cost of LOHC storage	€/kgH_2	50	[70,71]
$c_{S_{LOHC_{O\&M}}}$	O&M cost of LOHC storage	%	2	[70,71]
$D_{min_{LOHC_{deh}}}$	Min size of LOHC dehydrogenation unit	kW$_{el}$	100	[70,71]
E_{LOHC}	Carbon footprint of LH_2 via ships	kg$_{CO2,eq}$/kgH_2	4.6	[66,69]
$k_{1_{LOHC_{deh}}}$	Proportionality coefficient of LOHC dehydrogenation unit	-	0.73	[70,71]
$k_{2_{LOHC_{deh}}}$	Proportionality coefficient of LOHC dehydrogenation unit	kWh/kg	0.37	[70,71]
$k_{max,LOHC_{deh}}$	Max power load of LOHC dehydrogenation unit	-	1	[70,71]
$k_{min,LOHC_{deh}}$	Min power load of LOHC dehydrogenation unit	-	0.3	[70,71]
$LT_{LOHC_{deh}}$	Lifetime of LOHC dehydrogenation unit	year	20	[70,71]
$LT_{S_{LOHC}}$	Lifetime of LOHC storage	year	20	[70,71]

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