Green Ammonia Downstream

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June 29, 2022

Sets

N set of nodes in network fleet model
(a node represents where a ship can be at any time and where the port flow is operated)
$N^{Ports} \subset N$ subset of nodes that are ports (can either import or export ammonia)
$N^{Ocean} \subset N$ subset of nodes that are traveling nodes(in ocean= no demand)
$N^{Region} \subset N$ subset of nodes that are supply and demand nodes
$N^{ShipNodes} \subset N$ subset of nodes that are accessible by a ship in the network (N^{Ports} and N^{Oc}
$N^{PortNodes} \subset N$ subset of nodes that are accessible by a port in the network (N^{Ports} and N^{Re}
S set of ships that can be built in the simulation
M set of ship model types that can be built
T set of timesteps to simulate optimization model (daily or hourly basis)

Parameters

c_m^{Ship} CAPEX for ship model m
$c^{PortCapacity}$ CAPEX for port on kg basis import NH3
$c^{PortStorage}$ CAPEX for port storage on kg basis NH3

$o_m^{ShipFixed}$ Fixed OPEX for ship type m
$o^{PortCapacityFixed}$ Fixed OPEX for port on kg basis NH3
$o^{PortStorageFixed}$ Fixed OPEX for port storage on kg basis NH3

$o_m^{ShipVariable}$ Variable OPEX for ship type m (fuel costs)

b_m bulk size of ship model m (how much ammonia can it carry)

$d_{r,t}$ demand for fuel in region r at timestep t (positive for supply and negative for demand)

$l_{i,j}$ length (or distance) from port i to port j $\forall i \in P, j \in P \setminus i$

$i_{p,r}^{Region}$ indicator parameter on whether port p is in region r. If it is, value is 1, else, value is 0

δ speed of ships (assume all ship speeds are similar and constant)

n lifetime of ships (years to run simulation for)

i discount rate

g_{EY} equivalent lifetime of ship or port at NPV terms
(includes the discount rate and lifetime of ship/port).
$g_{EY} = \frac{(1+i)^n-1}{i(1+i)^n}$

Decision Variables

$X_{s,m}$ whether to build ship s in simulation as model m (1-yes, 0-no) $\forall s \in S, m \in M$

$FL^{Ship}_{s,i,j,t}$ amount of fuel to send from node i to node j for ship s at time t
$\forall s \in S, i, j \in N^{ShipNodes}, t \in T$

$FA^{Ship}_{s,i,t}$ amount of fuel available for ship network s at node i at time t
$\forall s \in S, i \in N^{Ocean}, t \in T$

$SL_{s,i,t}$ binary indicator variable for ship s location at node i at time t
$\forall s \in S, i \in N^{ShipNodes}, t \in T$

$FL^{Storage}_{i,j,t}$ amount of fuel to send from port accessible node i to port accessible node j for ship
$\forall i \in N^{PortNodes}, t \in T$

$FA^{Port}_{i,t}$ amount of fuel available at port p at time t
$\forall i \in N^{Port}, t \in T$

$C^{Storage}_{i}$ capacity storage for port node i (how much fuel can be held at the port) $\forall i \in N^{Port}$
$C^{Transfer}_{i}$ capacity for import export of port node i (how much fuel can be moved through the

Optimization Model

Objective

$$\min \quad CS^{Costs} + PS^{Costs} \tag{1}$$

where

$$\begin{aligned} CS^{Costs} = &\sum_{s \in S} \sum_{m \in M} (c^{Ship}_{m} X_{s,m} + g_{EY}(o^{ShipFixed}_{m} X_{s,m} + \\ &\sum_{i \in N^{ShipNodes}} \sum_{j \in N^{ShipNodes} \setminus i} \sum_{t \in T} (o^{ShipVariable}_{m} l_{i,j} FL^{Ship}_{s,i,j,t})) \end{aligned} \tag{2}$$

$$\begin{aligned} PS^{Costs} = \sum_{p \in N^{Port}} &(C^{Storage}_{p}(c^{PortCapacity} + g_{EY} o^{PortCapacityFixed}) + \\ &C^{Transfer}_{p}(c^{PortStorage} + g_{EY} o^{PortStorageFixed})) \end{aligned} \tag{3}$$

S.t.

$$\sum_{m\in M} X_{s,m} \leq 1 \qquad \forall s \in S \tag{4}$$

$$\sum_{i\in N^{ShipNodes}} SL_{s,i,t} = \sum_{m\in M} X_{s,m} \qquad \forall s \in S, t \in T \tag{5}$$

$$FL^{Storage}_{i,j,t} \leq l_{i,j} \sum_{p\in N^{Ports}} C^{Storage}_{p} \qquad \forall s \in S, i, j \in N^{PortNodes}, t \in T \tag{6}$$

$$FL^{Ship}_{s,i,j,t} \leq SL_{s,i,t} l_{i,j} \sum_{m\in M} b_m \quad \forall s \in S, i, j \in N^{ShipNodes}, t \in T, FL^{Ship}_{s,i,j,0} = 0 \tag{7}$$

$$SL_{s,j,t} \leq \sum_{i\in N^{ShipNodes}} SL_{s,i,t-1} l_{i,j} \sum_{m\in M} b_m \quad \forall s \in S, i, j \in N^{ShipNodes}, t \in T, SL_{s,i,0} \geq 0 \tag{8}$$

$$FA^{Ship}_{s,i,t} = FA^{Ship}_{s,i,t-1} + \sum_{j\in N^{ShipNodes}} (FL^{Ship}_{s,j,i,t-1} - FL^{Ship}_{s,i,j,t-1})$$
$$\forall s \in S, i \in N^{Ocean}, t \in T, FA^{Ship}_{s,i,0} = 0 \tag{9}$$

$$\sum_{s\in S} \sum_{j\in N^{Ocean}} (FL^{Ship}_{s,j,i,t} + FL^{Ship}_{s,i,j,t}) \leq C^{Transfer}_{i} \qquad \forall i \in N^{Port}, t \in T \tag{10}$$

$$FA^{Port}_{i,t} \leq C^{Storage}_{i} \qquad \forall i \in N^{Port}, t \in T \tag{11}$$

$$FA^{Port}_{p,t-1} + \sum_{r\in N^{Region}} i_{p,r}(FL^{Storage}_{r,p,t-1} - FL^{Storage}_{p,r,t-1}) +$$
$$\sum_{s\in S} \sum_{i\in N^{Ocean}} (FL^{Ship}_{s,i,p,t-1} - FL^{Ship}_{s,p,i,t-1}) = FA^{Port}_{i,t} \quad \forall p \in N^{Port}, t \in T, FA^{Port}_{i,0} = 0 \tag{12}$$

$$\sum_{r \in N^{Region}} (FL_{p,r,t}^{Storage}) + \sum_{s \in S} \sum_{i \in N^{Ocean}} (FL_{s,p,i,t}^{Ship}) \leq FA_{i,t}^{Port} \quad \forall p \in N^{Port}, t \in T \tag{13}$$

$$\sum_{p \in N^{Port}} i_{p,r}(FL_{p,r,t}^{Storage} - FL_{r,p,t}^{Storage}) = d_{r,t} \qquad \forall r \in N^{Region}, t \in T \tag{14}$$

$$\begin{aligned} & X_{s,m}, SL_{s,i,t}, i_{p,r}^{Region} \in \{0,1\} \\ & \forall s \in S, m \in M, i \in N^{ShipNodes}, t \in T, p \in N^{Port}, r \in N^{Region} \end{aligned} \tag{15}$$

All other decision variables are non negative reals

Objective and Constraint Explanations

1. Minimize cargo ship costs and port costs
2. Ship costs are equal to CAPEX construction costs (depends on model type) + fixed operation costs (discounted into the future) + variable operation costs (which depends on which routes served over the year and also discounted into future)
3. Port costs are equal to CAPEX constructions costs (port capacity costs) + fixed operation costs (for both capacity and storage segments-discounted into future)
4. Ship decision variable: can only select at max 1 model to build for each ship
5. Ship location build requirement: If you build a ship then the ship must be located at one of the ship nodes
6. Ship flow connection: node must be connected for ammonia to flow
7. Ship flow location connection: ship must be at the home node in order for flow to move

8. Ship movement definition: ship can only move from node to node
9. Ship fuel available definition: fuel available for ship s at a node is equal to previous capacity + any inflows - any outflows
10. Port Capacity definition: port must be large enough to handle total inflows and outflows from ships
11. Capacity Storage definition: port capacity must be large enough to contain available fuel
12. Fuel available port definition: current fueal available equal previous + any demand flow changes + any ship flow changes (inflow is positive and outflow is negative)
13. Fuel deployment definition: must have enough fuel to deploy to meet demand and load onto ships
14. Meet demand rule: fuel deployed from port or loaded into port must be equal to demand
15. Bound constraints: listed decision variables are binary and all other decision variables are non negative reals