Green Ammonia Downstream

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June 14, 2022

Sets

R set of regions r that import/export ammonia (can be countries or specific regions)
P set of ports p in the simulation
M model types for transport ships that can be built
S set of number of ships that can be built for model type in simulation
(default set to 100, i.e. you can build up to 100 ships for the simulation)
T set of timesteps to simulate optimization model (daily 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 region r at timestep t (positive means demand, negative means supply)

$l_{i,j}$ 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) $\forall s \in S, m \in M$

$B_{s,i,j,t}$ whether to send ship s from terminal i to terminal j at timestep t
(1-ship leaves home port i at t, 0-ship not put on route)
$\forall s \in S, i \in P, j \in P \setminus i, t \in T$

$i^{InPort}_{s,p,t}$ indicator variable on whether ship s is at port p at timestep t
$\forall s \in S, r \in R, p \in P, t \in T$ (1-true, 0-no)

$i^{IsTraveling}_{s,t}$ indicator variable on whether ship s at timestep t is en route (1-en route (unable f
$\forall s \in S, p \in P, t \in T$ (1-true, 0-no)

$CS^{Avail}_{s,t}$ amount of ammonia available to deploy on cargo ship s at timestep t
$\forall s \in S, t \in T$

$CS^{Deploy}_{s,t}$ amount of ammonia to deploy (unload) from cargo ship s at timestep t
$\forall s \in S, t \in T$

$PS^{Avail}_{p,t}$ amount of ammonia able to be deployed at port storage p at timestep t
$\forall p \in P, t \in T$

$PS^{Deploy}_{p,t}$ amount of ammonia to deploy from port storage p at timestep t to meet demand
$\forall p \in P, t \in T$

$CT_{s,p,t}$ amount of cargo (ammonia) to transfer from ship s at port p at time t (positive mean

$PS^{PortCapacity}_{p}$ ammonia unloading capacity at port p $\forall p \in P_r$
$PS^{StorageCapacity}_{p}$ ammonia storage capacity at port p $\forall p \in P_r$

Optimization Model

Objective

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

where

$$CS^{Costs} = \sum_{s \in S} \sum_{m \in M} (c_m^{Ship} X_{s,m} + g_{EY}(o_m^{ShipFixed} X_{s,m} + \sum_{i \in P} \sum_{j \in P \setminus i} \sum_{t \in T} (o_m^{ShipVariable} l_{i,j} B_{s,i,j,t}))) \tag{2}$$

$$\begin{aligned} PS^{Costs} = \sum_{p \in P} (PS_p^{PortCapacity} (c^{PortCapacity} + g_{EY} o^{PortCapacityFixed}) + \\ PS_p^{StorageCapacity} (c^{PortStorage} + g_{EY} o^{PortStorageFixed})) \end{aligned} \tag{3}$$

S.t.

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

$$B_{s,i,j,t} \leq \sum_{m \in M} X_{s,m} \qquad \forall s \in S, i \in P, j \in P \setminus i, t \in T \tag{5}$$

$$B_{s,i,j,t} \leq i^{InPort}_{s,i,t} \qquad \forall s \in S, i \in P, j \in P \setminus i, t \in T \tag{6}$$

$$i^{IsTraveling}_{s,t} = \sum_{p \in P} (i^{InPort}_{s,p,t-1} - i^{InPort}_{s,p,t}) + i^{IsTraveling}_{s,t-1} \qquad \forall s \in S, t \in T,$$

$$\sum_{p \in P} i^{InPort}_{s,p,0} = 1, i^{IsTraveling}_{s,0} = 0 \tag{7}$$

$$\sum_{p \in P} i^{InPort}_{s,p,t} = 1 - i^{IsTraveling}_{s,t} \qquad \forall s \in S, t \in T \tag{8}$$

$$\sum_{t=t_0}^{t_0+\left\lceil \frac{l_{i,j}}{\delta} \right\rceil} i^{InPort}_{s,j,t} = B_{s,i,j,t_0} \qquad \forall s \in S, i \in P, j \in P \setminus i, t_0 \in T \tag{9}$$

$$i^{InPort}_{s,j,t+\left\lceil \frac{l_{i,j}}{\delta} \right\rceil} = B_{s,i,j,t} \qquad \forall s \in S, i \in P, j \in P \setminus i, t_0 \in T \tag{10}$$

In above two constraints, if $t + \left\lceil \frac{l_{i,j}}{\delta} \right\rceil \geq$ T set length then: $i^{InPort}_{s,j,t+\left\lceil \frac{l_{i,j}}{\delta} \right\rceil} = 0$ (i.e., you can't send a ship to a destination port that is outside the simulation timeframe).

$$i^{InPort}_{s,p,t} \leq PS^{PortCapacity}_{p} \qquad \forall s \in S, p \in P, t \in T \tag{11}$$

$$CS^{Avail}_{s,t} \leq \sum_{m \in M} X_{s,m} b_m \qquad \forall s \in S, t \in T \tag{12}$$

$$CT_{s,p,t} \leq CS^{Avail}_{s,t} \qquad \forall p \in P, s \in S, t \in T \tag{13}$$

$$CT_{s,p,t} \leq i^{InPort}_{s,p,t} \sum_{m \in M} b_m \qquad \forall p \in P, s \in S, t \in T \tag{14}$$

$$CS^{Avail}_{s,t} = CS^{Avail}_{s,t-1} + \sum_{p \in P} CT_{s,p,t} \qquad \forall s \in S, t \in T, CS^{Avail}_{s,0} = 0 \tag{15}$$

$$\sum_{s\in S} CT_{s,p,t} \leq PS_p^{PortCapacity} \qquad \forall p \in P, t \in T \tag{16}$$

$$PS_{p,t}^{Avail} = PS_{p,t-1}^{Avail} + \sum_{s\in S} CT_{s,p,t} - PS_{p,t}^{Deploy} \quad \forall p \in P, t \in T, PS_{p,0}^{Avail} = 0 \tag{17}$$

$$PS_{p,t}^{Avail} \leq PS_p^{StorageCapacity} \qquad \forall p \in P, t \in T \tag{18}$$

$$PS_{p,t}^{Deploy} \leq PS_{p,t}^{Avail} \qquad \forall p \in P, t \in T \tag{19}$$

$$\sum_{p\in P} (i_{p,r}^{Region}(PS_{p,t}^{Deploy} + \sum_{s\in S} CT_{s,p,t})) = d_{r,t} \qquad \forall r \in R, t \in T \tag{20}$$

$$B_{s,i,j,t}, X_{s,m}, i_{s,i,t}^{InPort} \in \{0,1\} \quad \forall m \in M, s \in S, i \in P, j \in P_r \setminus i, t \in T \tag{21}$$

All other decision variables are non negative reals (except for CT which can be positive or 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 route scheduling build requirement: In order to send a ship on a route you have to build it

6. Ship route scheduling availability: Ship must be at correct port to be able to schedule it
7. Ship traveling definition: ship is traveling if it leaves port (1-0 = 1-true), and not traveling if makes it to port (-1 + 1 =0-no longer traveling)
8. Only one port at a time: ship is either traveling and thus can not be at any other ports (if not at a port that means the ship is en route) or can be at one port
9. In port calculation: if you sent the ship to the port, it will be there in however many days it takes to be there (rounding up) and wont be in any other ports
10. Final port clarification: will be at the final port in however many days required
11. Port construction: can only have a ship in the port if the port is constructed
12. can only carry maximum capacity of ship
13. can only transfer as much ammonia as you have on board
14. only transfer ammonia if you are at the port (sum up model capacities just for placeholder)
15. How much ammonia you have available is previous amount plus any fuel transfers (can be positive or negative)
16. Can only transfer as much fuel as the port allows
17. Port Storage ammonia availability: equal to previous day + any fuel transfers - if you deploy any fuel to meet demand
18. Port storage ammonia capacity: can only store as much capacity size that you built
19. Port deploy ammonia: can only deploy as much ammonia as you have at port

20. The fuel deployed from port storage (only positive) and fuel transfer from ship to port (can be positive-unloading or negative-loading fuel) must equal demand (can be positive-consumption, or negative-supply)

21. Sending a ship, building one, keeping one at a port is a binary decision