# MULTISTAGE SYSTEM PLANNING FOR HYDROGEN PRODUCTION AND DISTRIBUTION

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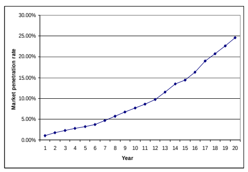
## Summary:

Hydrogen is an energy carrier that has the potential to improve the sustainability of transportation fuels and reduce oil dependence. This study presents a stochastic dynamic programming model for sequentially building a hydrogen production and distribution system. The decision variables are the *sequence* and *locations* of the central production sites and the corresponding distribution systems from the supply to the demand sites. The plant construction time (i.e. two years) is also considered.


A ***case study*** based on the geographic setting of Northern California is included, in which the hydrogen is produced via coal gasification and transported from plant to city gates (demand sites) by cryogenic liquid hydrogen trucks. The future demands for hydrogen are modeled as uncertain parameters, with an assumption that hydrogen fuel cell vehicle (HFCV) market penetration increases from 1% to 25% over a 20-year period. This model provides multistage decision support for long term transportation energy planning at national and regional levels.

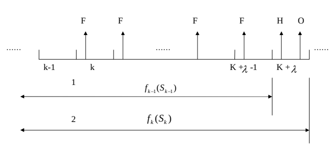



## Method:

A two-level *stochastic dynamic programming* model was proposed to optimize the process of building up and operating hydrogen production facilities during the transition to a hydrogen–based transportation system. The objective of the model is to minimize the total system cost, which consists of capital and operation costs for hydrogen production and distribution infrastructure throughout the entire 20-year planning horizon.

Total system cost = ( **Capital cost** -location -size/number ) + ( **Operation cost** -production -delivery -penalty cost )

***Model formulation*** *(dynamic programming+ stochastic programming)*




$$f_k(S_k) = \min_{j \in S_k \cup \phi} \{ \lambda F_j z_j^k + H^*_{k+\lambda}(S_k) + O^*_{k+\lambda}(S_k) + f_{k-1}(S_{k-1}) \}$$

— ***Dynamic programming model***

- minimum accumulative total system cost from the beginning of the planning horizon until the end of time stage $k+\lambda$
- Capital cost of plants under construction
- Total capital cost of effective plants

$$S_{k-1} = \begin{cases} S_k & if \;\; j \in \{\phi\} \\ S_k - \{j\} & if \;\; j \in S_k \end{cases}$$

Boundary condition:

$$f_0(S_0) = \sum_{k=1}^{\lambda} \left( H_k^*(S_0) + O_k^*(S_0) \right)$$

Expected operation cost ***- Stochastic submodel***

*Minimize*

$$O_k^*(S_{k-\lambda}) = E_\omega \left( \sum_j CP_j S_j^k(\omega) + \sum_j \sum_{i \in I} (CT_{ji} + \frac{Ct}{365}) \frac{x_{ji}^k(\omega)}{cap^T} + \sum_{i \in I} \alpha q_i^k(\omega) \right)$$

Subject to

$$D_i^k(\omega) - \sum_j x_{ji}^k(\omega) = q_i^k(\omega)$$

$$S_j^k(\omega) = \sum_{i \in I} xk_{ji}^k(\omega)$$

$$S_j^k(\omega) \le cap_j^p$$

It optimizes the production and distribution system at every time stage given the tentative plant location pattern (*Sk*) from the dynamic programming model

## Case Study Results:

***Baseline scenario***

(1) all plants have capacity of 500 tonnes/day
(2) penalty cost for demand shortages is $10/kg
(3) plant capital cost varies

| Plant | Location | Capital Cost (500 tonne/day) |
|---|---|---|
| Plant 1 | Kern County | $ 281,340,738 |
| Plant 2 (+20%) | San Jose | $ 337,608,886 |
| Plant 3 (+10%) | Moss Landing | $ 309,474,812 |
| Plant 4 (+20%) | Pittsburg | $ 337,608,886 |
| Plant 5 | Yuba City | $ 281,340,738 |

Results:

Year 1-5 Year 6-10 Year 11-15 Year 16-20

∗ Baseline result summary

| Year | Location (plant ID) | Under construction capital cost (2005$/year) | Effective plant capital cost (2005$/year) | Operation cost (2005$/year) | Production (tonnes/year) | Shortage (tonnes/yr) | Total system cost (2005$/year) | Annualized H2 cost (2005$/KG) | penalty cost % |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 5* | | | | | | | | |
| 1** | | $ - | $ 562,681,476.10 | $ 26,793,720.08 | 36,061.33 | 0.00 | $ 589,475,196.18 | $ 16.60 | 0% |
| 2 | | | | | | | | | |
| 3 | | $ - | $ 281,340,738.05 | $ 20,724,082.93 | 27,148.00 | 0.00 | $ 302,064,820.98 | $ 11.13 | 0% |
| 4 | | $ - | $ 281,340,738.05 | $ 29,978,377.79 | 39,360.32 | 0.00 | $ 311,319,115.84 | $ 7.91 | 0% |
| 5 | | $ - | $ 281,340,738.05 | $ 33,890,721.95 | 44,465.50 | 0.00 | $ 315,231,460.00 | $ 7.09 | 0% |
| 6 | | $ - | $ 281,340,738.05 | $ 44,115,545.70 | 57,798.25 | 0.00 | $ 325,456,283.75 | $ 5.63 | 0% |
| 7 | | $ - | $ 281,340,738.05 | $ 57,518,008.05 | 75,394.56 | 0.00 | $ 338,858,746.10 | $ 4.49 | 0% |
| 8 | | $ - | $ 281,340,738.05 | $ 73,413,580.45 | 96,186.90 | 0.00 | $ 354,754,318.50 | $ 3.69 | 0% |
| 9 | | $ - | $ 281,340,738.05 | $ 91,664,502.34 | 120,103.48 | 0.00 | $ 373,005,240.39 | $ 3.11 | 0% |
| 10 | | $ - | $ 281,340,738.05 | $ 107,222,057.83 | 140,505.97 | 0.00 | $ 388,562,795.88 | $ 2.77 | 0% |
| 11 | 1&5 | $ 281,340,738.05 | $ 281,340,738.05 | $ 145,064,124.24 | 155,956.57 | 2,619.50 | $ 707,745,600.34 | $ 4.54 | 4% |
| 12 | | $ 281,340,738.05 | $ 281,340,738.05 | $ 214,056,961.47 | 174,963.08 | 8,272.83 | $ 776,737,437.57 | $ 4.44 | 12% |
| 13 | | | $ 562,681,476.10 | $ 167,967,904.72 | 221,218.22 | 0.00 | $ 730,649,380.82 | $ 3.30 | 0% |
| 14 | | | $ 562,681,476.10 | $ 198,866,512.97 | 261,141.62 | 0.00 | $ 761,547,989.07 | $ 2.92 | 0% |
| 15 | | | $ 562,681,476.10 | $ 213,420,957.51 | 279,883.22 | 0.00 | $ 776,102,433.61 | $ 2.77 | 0% |
| 16 | 1,3 &5 | $ 309,474,811.86 | $ 562,681,476.10 | $ 288,752,272.41 | 311,329.02 | 5,080.33 | $ 1,160,908,560.37 | $ 3.73 | 4% |
| 17 | | $ 309,474,811.86 | $ 562,681,476.10 | $ 464,256,243.90 | 350,416.32 | 19,577.50 | $ 1,336,412,531.86 | $ 3.81 | 15% |
| 18 | | | $ 872,156,287.96 | $ 303,832,154.44 | 404,675.33 | 0.00 | $ 1,175,988,442.40 | $ 2.91 | 0% |
| 19 | | | $ 872,156,287.96 | $ 350,083,978.36 | 444,073.46 | 1,596.67 | $ 1,222,240,266.32 | $ 2.75 | 1% |
| 20 | | | $ 872,156,287.96 | $ 449,640,028.04 | 473,272.66 | 9,298.17 | $ 1,321,796,316.00 | $ 2.79 | 7% |

Note: * Plant ID can be referred to Table 1 for its corresponding plant location.
**For the first two years, location pattern ($S_0$ in the DP model) has been determined right before the beginning of the first year and its corresponding costs are also given by the boundary condition. Therefore, the numbers in the second row of the table aggregate the results of the first two years.

***Identical plant capital cost scenario***

(1) all plants have capacity of 500 tonnes/day
(2) penalty cost for demand shortages is $10/kg
(3) Identical plant capital cost

Results:

∗ Results of identical plant capital cost scenario

| Scenarios | Total system cost (2005$) | Capital cost (2005$) | Operation cost (2005$) |
|---|---|---|---|
| Identical plant capital cost | $ 12,954,896,893.29 | $ 9,846,925,831.75 | $ 3,107,971,061.54 |
| Baseline | $ 13,268,856,935.97 | $ 9,987,596,200.80 | $ 3,281,260,735.17 |
| Difference in percentage | -2.37% | -1.41% | -5.28% |

Year 1-5 Year 6-10 Year 11-15 Year 16-20

***Variation of feedstock costs***

The cost of hydrogen production and distribution is dependent on the costs of several energy feedstocks that are used in the process.

Results:

| Scenarios | Total system cost (2005$) | capital cost (2005$) | operation cost (2005$) |
|---|---|---|---|
| Electricity price (2005$kWh) increase from 0.05 to 0.10 | $14,845,755,227.16 (+11.88%) | $9,987,596,200.80 (0%) | $4,858,159,026.36 (+48.06%) |
| Coal price (2005$/mmbtu) increases from 1.29 to 1.50 | $13,430,961,382.28 (+1.22%) | $9,987,596,200.80 (0%) | $3,443,365,181.48 (+4.94%) |
| Diesel fuel price (2005$/gal) from 2.00 to 4.00 | $13,297,891,865.54 (+0.22%) | $9,987,596,200.80 (0%) | $3,310,295,664.74 (+0.88%) |
| Baseline scenario | $13,268,856,935.97 | $ 9,987,596,200.80 | $ 3,281,260,735.17 |

## Discussions:

***Achievements and observations:***

➢Proposed an innovative method of integrating stochastic and dynamic programming models to optimize the sequence of siting hydrogen production facilities and simultaneously determine optimal location pattern in each time stage, under demand uncertainty .

➢the model may reserve the potential of allowing more flexible ways of modeling the operational process.

➢ A case study based on geographical settings of Northern California was examined. In general, we found that the capital cost was the major cost driver in the total system cost and varying feedstock costs could change operation cost significantly.

***What is to be done:***

➢An immediate extension of this work is to consider plant capacity as a planning decision variable.

➢Intermediate storage facilities can also be introduced into the system to store excessive produced hydrogen, when the production cost varies with time.

➢Develop efficient solution algorithm for extended work.

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