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Supply Chain Dynamics

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Hydrogen Valley Challenge

Group 9

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Part I: Strategic positioning and demand allocation

Based on the information given in the case, there are several plants and demand points. With the other information, the parameters are determined to set up a linear model with two decision variables.

$PLANTS = \{1, 2, 3, 4, 5, 6\}$
$DEMAND = \{1, 2, 3, 4, 5, 6, 7\}$
$c = 0.06$:constant cost per quintal per kilometer
$d_j,\ j \in DEMAND$: amount demanded of location j per day
$t_i,\ i \in PLANTS$: throughput production place i per day
$f_i,\ i \in PLANTS$: fixed costs using production place i per day
$v_i,\ i \in PLANTS$: variable costs producing hydrogen quintals at production place i
$k_{ij},\ i \in PLANTS,\ j \in DEMAND$: kilometers between production place i to demand point j
$x_{ij},\ i \in PLANTS,\ j \in DEMAND$: amount of hydrogen quintals from place i to demand point j
$y_i,\ i \in PLANTS$: binary variable indicating if the place i is open (1) or not (0)

$$minimize \sum_{i \in PLANTS}^{6} \sum_{j \in DEMAND}^{7} v_i x_{ij} + 2(c\, k_{ij} x_{ij}) + \sum_{i \in PLANTS}^{6} f_i y_i$$

$s.t.$

$\sum_{i \in PLANTS}^{6} x_{ij} \geq d_j,\ j \in DEMAND$: amount of hydrogen be bigger or equal to the demand j

$\sum_{j \in DEMAND}^{7} x_{ij} \leq t_i y_i,\ i \in PLANTS$: hydrogen quintals has to be smaller or equal to the throughput i

$x_{ij} \geq 0, i \in PLANTS,\ j \in DEMAND$: hydrogen quintals from plant i to demand j is non negative

$y_i \in \{0, 1\},\ i \in PLANTS$: set y to be an binary decision variable

a) Based on the linear model, the minimized objective will lead to rounded daily costs of €1218,-. Where demand points are severed by plants 1, 5 and 6. In the following combination.: x(1,1) = 36, x(1,3) = 11, x(1,6) = 30, x(5,3) = 23, x(5,4) = 50, x(5,5) = 27, x(6,2) = 42, x(6,7) = 43, y(1)=1, y(5) = 1, y(6) = 1.
b) In this situation an extra constraint is added to the model to make sure PLANT 6 has a minimum daily throughput of 90: $\sum_{j \in DEMAND}^{7} x_{6j} \geq 90$. This leads to rounded minimized daily costs of €1218,-.
c) An extra plant is added, including the benefits of the economies of scale in plant 6. Constraints are added to ensure that plant 6 or plant 7 can be opened: $y_6 + y_7 \leq 1$, and when the production of plant 6 is greater or equal to 80 than plant 7 must be opened: $\sum_{j \in DEMAND}^{7} x_{6,j} - 80 \leq My_7$. Which results in total daily costs of €1228,- where plants 1, 5 and 7 are opened.
d) The throughput constraint in the basic model as described in 1a is deleted, this leads to rounded daily costs of €842, all demand is served from plant 1.
e) To force plant 1 to open an extra constraint is added: $y_1 = 1$, this leads to the same rounded daily costs (€1218,-) as the basic model, because plant 1 is open in that situation already.

Part II: Reducing per unit cost of hydrogen in the Estonian hydrogen value chain

For calculating the unit price of (€/kg) H2, the process of hydrogen and delivery must be known. The process is based on how much the solar panels can produce. Since solar panels run on sun hour, we make a solar generation distinction between the four seasons. For the electrolyzer, we have made calculations for two different electrolyzers: Alkaline electrolysis cells (AEC) and solid oxide electrolysis cells technology (SOEC). Whereas the AEC has lower capital costs and the SOEC is more energy efficient (Nami et al., 2022). After the H2 is produced with the electrolyzer, it is transported to the customers in Tartu and Latvia. For both electrolyzers, three scenarios were written; low, medium, and high costs. The costs are based on Nami et al.'s article (2022). We calculate the price per hydrogen unit over two years (the project duration) and 25 years (the lifetime of the electrolyzers).

Alkaline electrolyzer cells (AEC)

For the AECs the initial CAPEX ranges from €600 → €950 → €1300 (from low to high cost) based on the market prices. The initial energy consumption (kWh/kg H2) ranges from 49 → 53 → 57 (low to high). For all three scenarios, the output per kg H2/h should be calculated based on the sun hours per season calculated previously and the efficiency of the electrolyzer (55%). The average kg per hour over the year is then calculated for the three scenarios. Range from 1.60 → 1.48 → 1.38 (low to high costs). We take into account the production constraint of 100kg per day. The CAPEX for one year is calculated by summing the kWh for all seasons times the initial CAPEX divided by two years. Ranging from €171,322.81→ €271,261.12 → €371,199.43 (from low to high costs).

Next, the OPEX calculations are made for the ongoing day-to-day costs to keep the electrolyzer running. The OPEX percentages are based on the article by Nami et al. (2022). The scenarios are based on taking percentages from the initial CAPEX calculated previously. See below the table for the three scenarios for the AECs electrolyzer and the eventual unit price of (€/kg) for hydrogen.

Table 1: overview price per unit hydrogen for AEC

AEC OPEX (2 year)		**Low-cost**	**Medium-cost**	**High-cost**
Stack replacement cost (50% of CAPEX) (10-year lifetime)	50%	€8,566.14	€13,563.06	€18,559.97
Maintenance (2%) (CAPEX 4-year)	2%	€3,426.46	€5,425.22	€7,423.99
Onside costs				
- Installation costs: (33%)	33%	€56,536.53	€89,516.17	€122,495.81
- Piping costs (35%)	35%	€59,962.98	€94,941.39	€129,919.80
- Instruction and controls (12%)	12%	€20,558.74	€32,551.33	€44,543.93
- Electrical equipment and material (13%)	13%	€22,271.97	€35,263.95	€48,255.93
Manufacturing costs				
- Labour costs (11.166 EUR/Year) (0.5 FTE)	0.5	€5,583.00	€5,583.00	€5,583.00
- Water costs (100kg hydrogen * 9 liters * 0,00412/Year)	0.00412	€1,353.42	€1,353.42	€1,353.42
OPEX (1-year)		€178,259.23	€278,197.54	€378,135.85
CAPEX + OPEX (1-year)		€349,582.05	€549,458.66	€749,335.27
euro/kg h2 per 2 years		€44.12	€64.07	€86.34
euro/kg h2 per 25 years		€21.68	€25.64	€29.78

Solid oxide electrolysis cells technology (SOEC)

We make the same distinction in scenarios for the SOECs ranging from low to high costs. The initial CAPEX (€/kW) ranges from €2000 - €3800 - €5600 based on the same article (Nami et al., 2022). We use the same article to create coherent financial statements. The energy consumption (kWh/kg H2) ranges from 34 → 34.5 → 35 (low to high costs). Noticeably, the initial CAPEX for SOEC is higher, but the energy consumption is lower than AEC. The same calculations are made for SOEC. The average kg/h over the year ranges from 2.31 → 2.28 → 2.24 (from low to high costs). Noticeable is that the output per kg H2/h is higher, and thus average kg/h (over the whole year) is higher than that for AEC. Therefore, we can state that SOEC produces more hydrogen. However, the CAPEX over one year is much higher, ranging from €571,076.04 → €1,085,044.48 → €1,599,012.92 (from low to high costs). This is about 233% higher than the CAPEX cost for the AEC.

Then the calculations are made for the OPEX. The OPEX percentage is based on the article by Nami et al. (2022). The scenarios are based on the initial CAPEX calculated previously. See below the graph for the three scenarios for the AECs electrolyzer and the eventual unit price of (€/kg) for hydrogen.

Table 2: overview price per unit hydrogen for SOEC

SOEC OPEX (2-year)		**Low-cost**	**Medium-cost**	**High-cost**
Stack replacement cost (23,5% per year) (5-year lifetime)	23.50%	€26,840.57	€50,997.09	€75,153.61
Maintenance (2%) (CAPEX 4-year)	2%	€11,421.52	€21,700.89	€31,980.26
Onside costs				
- Installation costs: (33%)	33%	€188,455.09	€358,064.68	€527,674.26
- Piping costs (35%)	35%	€199,876.61	€379,765.57	€559,654.52
- Instruction and controls (12%)	12%	€68,529.13	€130,205.34	€191,881.55
- Electrical equipment and material (13%)	13%	€74,239.89	€141,055.78	€207,871.68
Manufacturing costs				
- Labour costs (11.166 EUR/Year) (0.5 FTE)	0.5	€11,166.00	€11,166.00	€11,166.00
- Water costs (100kg hydrogen * 9 liters * 0,00412/Year)	0.00412	€1,353.42	€1,353.42	€1,353.42
OPEX (1-year)		€581,882.23	€1,094,308.77	€1,606,735.30
CAPEX + OPEX (1-year)		€1,152,958.28	€2,179,353.24	€3,205,748.21
euro/ kg h2 per 2 years		€70.78	€123.32	€177.34
euro/ kg h2 per 25 years		€25.30	€29.84	€34.49

The quantitative model used to calculate the unit price (€/kg) of hydrogen is an excel sheet. Excel allows for a representation of reality using mathematical financial formulas (SENACEA, n.d). This allows for an in-depth analysis of the problem and gives quick results. Using excel also allows us to change numbers/percentages so we can control our formulas and quickly see what would happen if we change certain inputs and what effect it has on the price of hydrogen. Using excel gives us a clear overview of all the data we have used to calculate the price of hydrogen.

Transportation cost:

To calculate the truck's distribution costs, we must establish the schedule first. In the case of Tartu city, we have determined that the driver requires 15 minutes to travel to and from the fuel station, including the time to unload the hydrogen. Based on the city's demand, the company needs to deliver 112 containers per year, a container must be delivered every three days, resulting in a total of 122 trips per year. Total transport costs are based on the truck's km fuel cost and a truck driver's personnel costs per year. By dividing the total transportation cost by the demand, the price per kilogram of hydrogen transport is €0.02.

For Latvia, it takes much longer to arrive at the fuel stations, 3 hours, including unloading the hydrogen. Based on the country's demand, the company needs to deliver 100 containers per year every 3.5 days, resulting in 105 trips per year. The price per kg of hydrogen for transport then becomes €0.14. This will be added to the overall price per kg.

Opportunities and suggestions

To decrease the overall cost of the hydrogen ecosystem, we can take a look at the entire supply chain. Many factors play a role in the financial costs of the supply chain. There are transportation costs from the park to Tartu City and Latvia. Storage costs are where the hydrogen is stored before transportation. The compressor is where the hydrogen is compressed into either gas or liquid. Although there are many costs associated with the supply chain of hydrogen, most of the costs (and costs that could be produced) come from the production of hydrogen (solar/grid and the electrolyzer). Below are three suggestions the company can make to decrease the overall supply chain costs.

Suggestion 1: Implement TPM

In the first scenario, we look at implementing total productive maintenance (TPM) that will limit breakdowns, delays, and slow speed. Basing our findings from an article by World class manufacturing (n.d.), we have estimated that implementing TPM costs about €50,000. Therefore, we create three scenarios ranging from low to medium to high costs over two years. The calculations below are based on the AEC electrolyzer, as it has the lowest cost compared to SOEC (see appendix A). TPM is necessary to prevent poor maintenance, affecting breakdown, set-up adjustment, speed, quality defect, and stoppage losses (EPA, 2022). TPM can help with these losses by keeping machinery functioning optimally and preventing equipment from breakdowns by making the equipment more efficient (EPA, 2022). TPM can also help the employees work more efficiently by training employees to understand the equipment better and connect the employees with the tools productively and efficiently to make the employees as effective as possible (Chris, 2020). Therefore, we expect the efficiency of the electrolyzer to increase from 55% to 75% after implementing TPM. See below the table for the calculations. Despite the high investment costs, there is a significant decrease in the costs per €/kg hydrogen.

Table 3: Scenario of Implementing TPM on electrolyzer AEC

Scenario 1: implement TPM AEC		**Low-cost**	**Medium-cost**	**High-cost**
- current costs per euro/kg h2 at 55% efficiency		€42.78	€63.25	€85.89
- TPM costs per year	€50,000.00	€399,582.05	€599,458.66	€799,335.27
- possible costs per euro/kg h2 at 75% efficiency		€29.74	€45.94	€63.65
Difference current vs TPM (%)		-30.48%	-27.36%	-25.90%

Table 3: Scenario of Implementing TPM on electrolyzer AEC

Suggestion 2: Grey energy

For the second suggestion to decrease cost we suggest the company to change from green grid energy to grey grid energy. Grey energy is produced at a lower cost as it is created from natural gas. Grey energy is created using steam methane reformation but without the greenhouse gasses created in the process (Naturalgrid, 2022). Green hydrogen produced by the grid comes from renewable sources such as solar or wind. Although green hydrogen is often classified as 'the cleanest form of hydrogen,' it also has negative aspects. Green hydrogen requires more energy than other fuels and is more expensive to generate (IBERDROLA, n.d). The cost of grey energy is €0.173 (GlobalPetrolPrices, 2022). Meanwhile, green energy costs between €1.26 and €1.46 (Clifford, 2022; Patel, 2020; Bellini, 2022). Only in fall and winter is there a shortage (kW), and is it required to use the grid energy. This is because the sun's hours are insufficient to deliver the required energy. Since the grid price decreases so drastically the total energy cost required from the grid decreases by 86% for the low-cost scenario. Find below the calculations.

Table 4: Scenario of using grey energy

Solar & Grid		Low cost	Medium cost	High-cost
Grid price (renewable energy)		€1.26	€1.36	€1.46
Total grid price for shortage		€1,613.30	€1,732.00	€1,850.70
Scenario 2: Grey energy				
Grid price (grey energy)		0.173	0.173	0.713
Total grid price for shortage		€225.71	€225.71	€225.71
Difference (in %)		-86.01%	-86.97%	-87.80%

<u>Suggestion 3: Selling excess solar energy</u>

Another suggestion that the company could make use of is the selling of excess solar energy. In the spring and summer seasons, there is an excess of solar energy (kW) as there is an excess amount of sun hours that are not used by the solar panels. The company could look at other manufacturers or countries wanting to buy the excess solar energy. Selling excess solar energy promotes environmental conservation, as no solar energy goes to waste (FMB, 2022). Now solar energy will be used on other products rather than non-green energy. Residential solar energy costs, on average, 6-8 cents per kWh (Solar.com, n.d.). However, the cost is based on various factors, e.g., the size of the solar system and sunlight. The money they make from this sale could be used for investments into the effectiveness of the supply chain and will lower the overall cost of the hydrogen supply chain.

Table 5: Scenario of selling excess solar energy

Scenario 3: Selling excess solar energy		Low	Medium	High
Price solar energy		€0.06	€0.07	€0.08
Excess summer per day		€223.56	€260.82	€298.08
Excess summer season		€20,567.56	€23,995.48	€27,423.41
Excess spring per day		€149.43	€174.34	€199.24
Excess spring season		€13,747.74	€16,039.03	€18,330.31
Total profit per year		€34,315.29	€40,034.51	€45,753.72

Conclusion

We analyzed the possible total investment costs per kg of hydrogen over 2 and 25 years for a small scale hydrogen valley in Estonia. Based on our analysis, we observed that of the two electrolyzers, the AEC is the best choice regarding costs over 2 and 25 years. However, the SOEC outperforms the AEC in terms of less energy consumption and higher hydrogen production capacity. Besides the production, we found that the transportation of hydrogen plays a minor role in terms of costs, only accounting for 0,14 per kg of hydrogen.

For this project, different possibilities and opportunities exist. We mainly looked at reducing costs by suggesting the implementation of TPM, taking gray energy from the grid instead of green energy, and selling excess solar energy. The TPM would be our main suggestion for reducing possible costs for AEC by 25-30% over two years. Next to these suggestions, we researched more different scenarios, which can be found in appendix B and C.

Overall, we can conclude that the price of hydrogen for the first two years for AEC will be between 47,- and 99,- euros/kg, producing a total between 23,000 → 28,000 kg of hydrogen, and between 72,- and 187,- euro/kg producing in total around 40,000 kg of hydrogen for the SOEC. Although the SOEC is more expensive over two years compared to the AEC, the extra production and possible implementation of our suggestions can make the SOEC less expensive considering the lifetime of 25 years, making the SOEC a possible better investment decision over the long term.

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Appendix A - Suggestion 1: implement TPM for SOEC

The implementation of the TPM on the SOEC resulted in the initial higher costs per kg hydrogen. This is due to the already high production capacity of the SOEC at 55% efficiency. Meaning that an increase in efficiency (to 75%) does result in an cost reduction for the SOEC

Table 6: implement TPM for SOEC

Scenario 1: implement TPM SOEC (2 years)		**Low-cost**	**Medium-cost**	**High-cost**
- current costs per euro/kg h2 at 55% efficiency		€56.95	€109.23	€163.01
- TPM costs per year	50000	€1,202,958.28	€3,382,311.52	€6,588,059.73
- possible costs per euro/kg h2 at 75% efficiency		€43.58	€124.32	€245.66
Difference current vs TPM		-23.49%	13.81%	50.71%

Appendix B - Scenario 4: Extra solar plant investment of 150 kWh

Besides the implementation of the TPM, we also researched the possible investment into an extra 150 kWh capacity into the current solar park. Based on Tables 7 and 8, we observed that the AEC profits the most from this investment compared to the SOEC in terms of cost reduction. This is due to the fact that the SOEC has a lower energy consumption, thereby, being less reliant on the grid.

Table 7: extra investment in the solar park for AEC scenario

Scenario 4: Extra 150 kWh solar investment AEC				
Investment per year		€81,500.00	€100,000.00	€131,250.00
CAPEX + OPEX (1-year) including solar investment		€431,082.05	€649,458.66	€880,585.27
euro/kg h2 (2 years)		€30.69	€50.01	€72.92
euro/kg h2 (25 years)		€2.91	€4.49	€6.36

Table 8: extra investment in the solar park for SOEC scenario

Scenario 4: Extra 150 kWh solar investment SOEC				
- investment per year		€81,500.00	€100,000.00	€131,250.00
- CAPEX + OPEX (1-year) including solar investment		€1,234,458.28	€2,279,353.24	€3,336,998.21
euro/ kg h2 (2 years)		€60.98	€114.25	€169.68
euro/kg h2 (25 years)		€11.79	€16.15	€20.69

Appendix C - Scenario 5: Sell surplus of Hydrogen

As the SOEC has the highest cost compared to the AEC, it has a distinct disadvantage in terms of the costs. However, the SOEC is able to produce more hydrogen per kWh (see sheet). Therefore, based on the current calculations the SOEC produces a possible surplus of hydrogen. In this scenario, we researched possible market options for selling this surplus of hydrogen.

Table 9: sell the surplus of hydrogen scenario for AEC

Scenario 5: Sell surplus of hydrogen AEC				
Kg surplus		2697.33	1888.13	1192.51
Kg h2 price EU		€8.00	€7.00	€6.00
Possible profit		€21,578.61	€13,216.92	€7,155.05
Discount per kg h2		€1.34	€0.82	€0.45

Table 10: sell the surplus of hydrogen scenario for SOEC

Scenario 5: Sell surplus of hydrogen SOEC				
Kg surplus		7427.54	7203.60	6986.06
Kg h2 price EU		€8.00	€7.00	€6.00
Possible profit		€59,420.35	€50,425.21	€41,916.34
Discount per kg h2		€3.70	€3.14	€2.61

Based on table 9 and 10, we can observe that the SOEC produces a much higher surplus compared to AEC, resulting in a higher discount per kg h2. This means that if a possible extra demand can be created the SOEC will be more profitable compared to the AEC long-term. Next to the possible extra profit from the SOEC's surplus, there is a second advantage: the SOEC is better prepared for possible demand spikes.