Integrated, Innovative Renewable Energy – Hydrogen Systems and Applications Workshop

BENCHMARK ANALYSIS & PRE-FEASIBILITY STUDY FOR THE MARKET PENETRATION OF METAL HYDRIDE HYDROGEN COMPRESSORS

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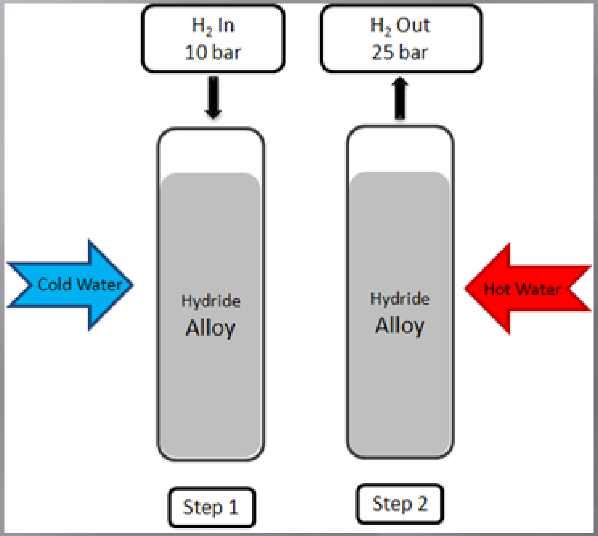
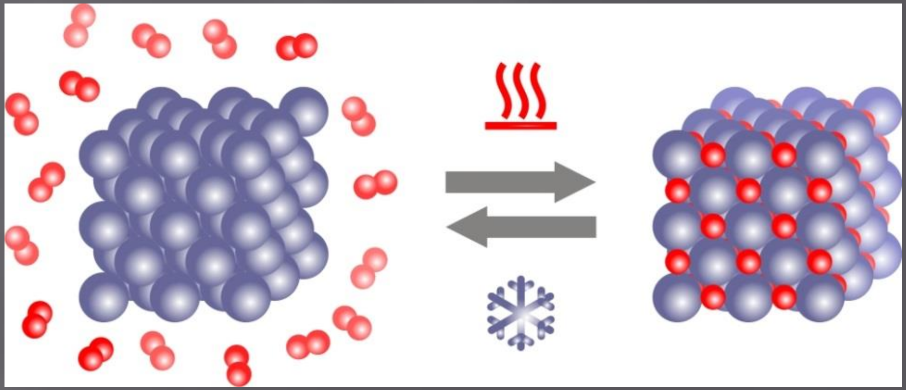
Metal Hydride Hydrogen Compressor (MH2C)

In general, a Metal Hydride Hydrogen compressor is a compressor that works by absorbing hydrogen at low pressure and temperature and desorbing it at a higher pressure by raising the temperature with an external heat source like a heated water bath. **Metal hydrides** are special alloys that can chemically store hydrogen in their metallic lattice.



Metal hydrides basic principle

This operating principle called thermal hydrogen compression system – based on the equilibrium pressure as a function of temperature and hydrogen content of the hydride – can offer an innovative economic alternative to traditional mechanical hydrogen compressors apart from the technical application for hydrogen storage in solid material.

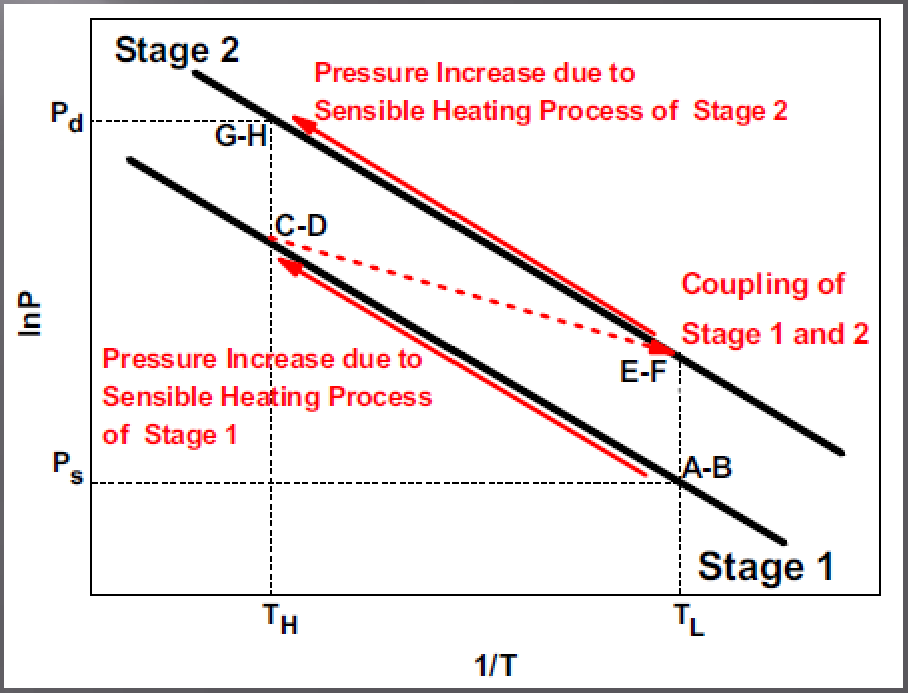


MH2C Advantages

Non-mechanical hydrogen compressors have several advantages over the mechanical ones, including:

- ✓ **smaller size**
- ✓ **lower noise levels**
- ✓ **lower operating and maintenance costs**
- ✓ **Increased efficiency (especially when using available heat wastes or excess renewable energy to feed the chemical compressor)**
- ✓ **Flexibility over a wide range of compression**

Moreover, since the hydrogen absorption-desorption plateau pressure of a metal hydride (MH) varies with temperature according to the van't Hoff equation ($\ln P = \Delta H/RT - \Delta S/R$), the MH compressors are thermally powered systems that use the ability of reversible metal hydrides to compress hydrogen **without any contamination**.



A van't Hoff plot illustrating the operation of a two-stage Metal Hydride Hydrogen Compression

Identification of Target Markets and other Market Issues

Based on the clear advantages of MH2C, we have identified two major niche markets

1. **RES & H2 autonomous power systems of islands and**
2. **Hydrogen filling stations for vehicles.**

A comparison from the economic point of view to the conventional (mechanical) hydrogen compressor, presented by DaCosta (2000), supports our identification.

Comparison of MH2Cand Mechanical Hydrogen Compressors

	MHH Compressor	Mechanical Compressor
Hydrogen Flow	56.63 Nm3/h	56.63 Nm3/h
Inlet Pressure	6.89 bar	6.89 bar
Outlet Pressure	248.2 bar	248.2 bar
Number of Stages	5	3
Weight	100 kg	3,600 kg
Volume	400 liters	6,000 liters
Hot Water Flow (waste heat)	50 gpm @ 90 C	-
Heat Energy Required	240 kBTU/h	-
Cooling Water Flow	50 gpm @ 30 C	20 gpm @ 30 C
Electrical Power	500 watts	20,000 watts
Estimated Capital Cost	€ 130,000	€ 145,000
Annual Power Cost (2,000 h/y, €0.10/kWh)	€100	€ 4,000
Annual Maintenance Cost	€1,000	€ 8,000

Comparison of MH2C & Mechanical Hydrogen Compressors

From the previous Table, it is evident that thermal Compressors offer significant advantages over mechanical compression:

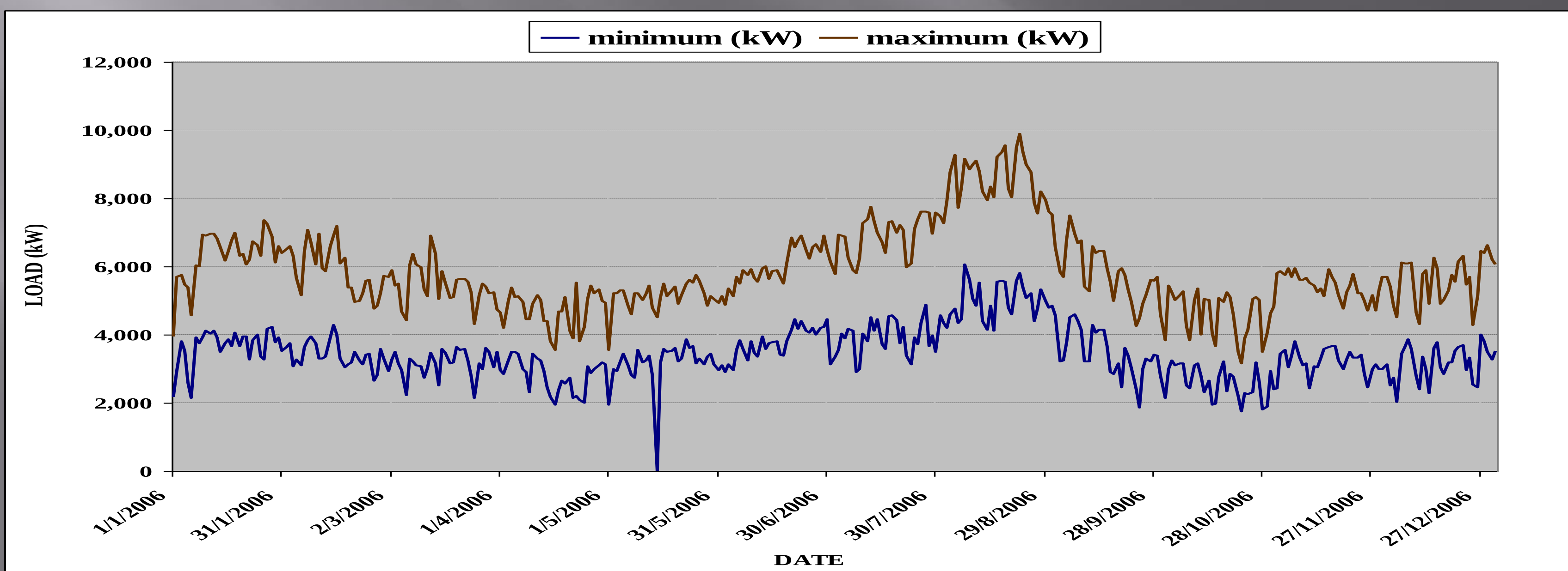
- They present significantly lower weight and volume compared to mechanical compressors
- They have slightly lower capital cost
- They have significantly lower operation and maintenance costs
- They consume significantly lower energy to operate
- Waste heat from renewable energy sources can be used in metal hydride compressors.

Integration of MH2C in an island micro-grid

- *Methodology and tools*
  - The simulation and optimisation of the case study has been performed by using the **HOMER software** tool by NREL
  - We used information and data on natural resources from the power system of Milos island (such as wind and solar irradiance data, electric and thermal loads, economic constraints, current and future equipment costs, user behaviour and control strategies)
  - The main purpose was to investigate the impact of diesel generators and batteries replacement with hydrogen technologies, including electrolysers, metal hydride hydrogen compressors, and fuel cells both in technical and financial terms.
- *Case study analysis*
  - The annual electricity demand of Milos island is approximately 39,729 MWh with peak demand equal to 8.5 MW. In order to meet this demand, the existing power system includes 8 thermal generator sets with a total capacity of around 11.25 MW and a small wind park comprising 3 wind turbines with a total installed capacity of 2.05 MW. Based on the simulation results, the existing power system delivers electricity at a cost equal to 113 €/MWh.

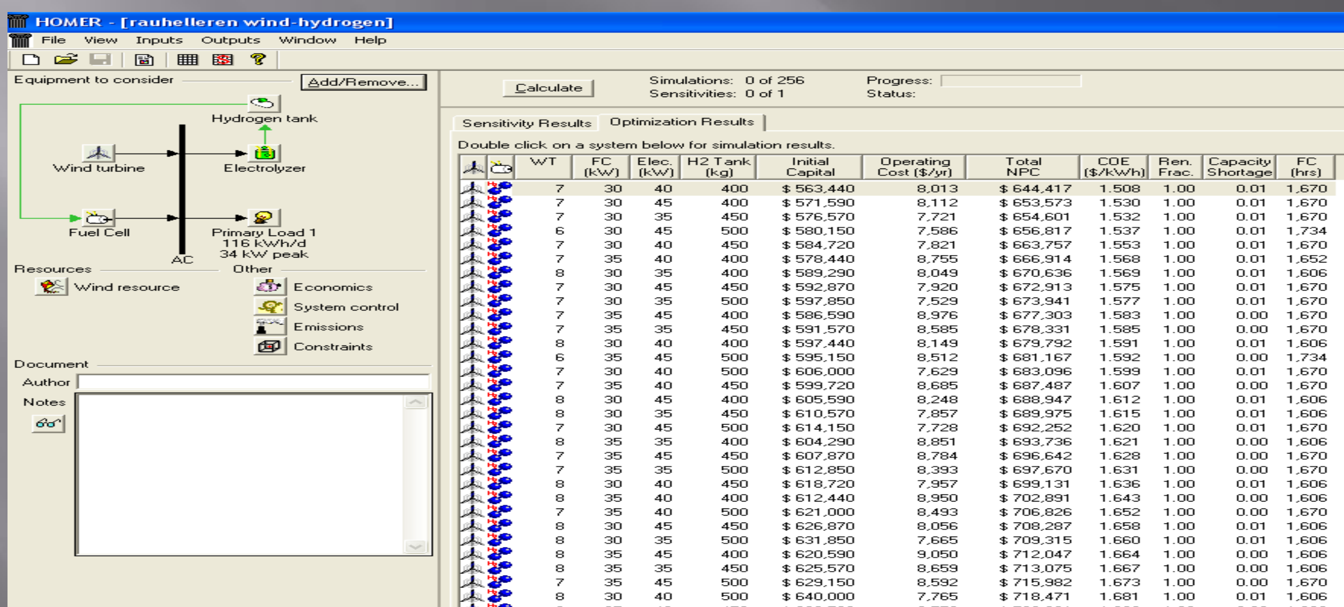
MILOS OVERVIEW

- Southwest part of the Aegean Sea, Cyclades
- 86 nautical miles from Athens
- Area: 151 km^2, Coastal line: 125 km
- 5.000 people live there permanently
- the population rises about 5 times during the summer period due to tourism



HOMER Software

- Developed by NREL, USA (http://www.nrel.gov/homer)
- Hybrid Optimization Model for Electric Renewables
- HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation (DG) applications.
- HOMER's optimization and sensitivity analysis algorithms allow you to evaluate the economic and technical feasibility of a large number of technology options.



Architecture of the existing power system

- 8 Thermal Generator Sets

2 Sulzer 7TAF48 Units (1,75 MW each, Heavy Oil)

3 MAN G9V30/45 Units (0,7 MW each, Heavy Oil)

1 CKD 12V27,5-B8S Unit (2 MW, Diesel)

1 CKD 12V27,5-B8S Unit (1,9 MW, Diesel)

1 FINCANTIERI BL230.12P Unit (1,75 MW, Diesel)

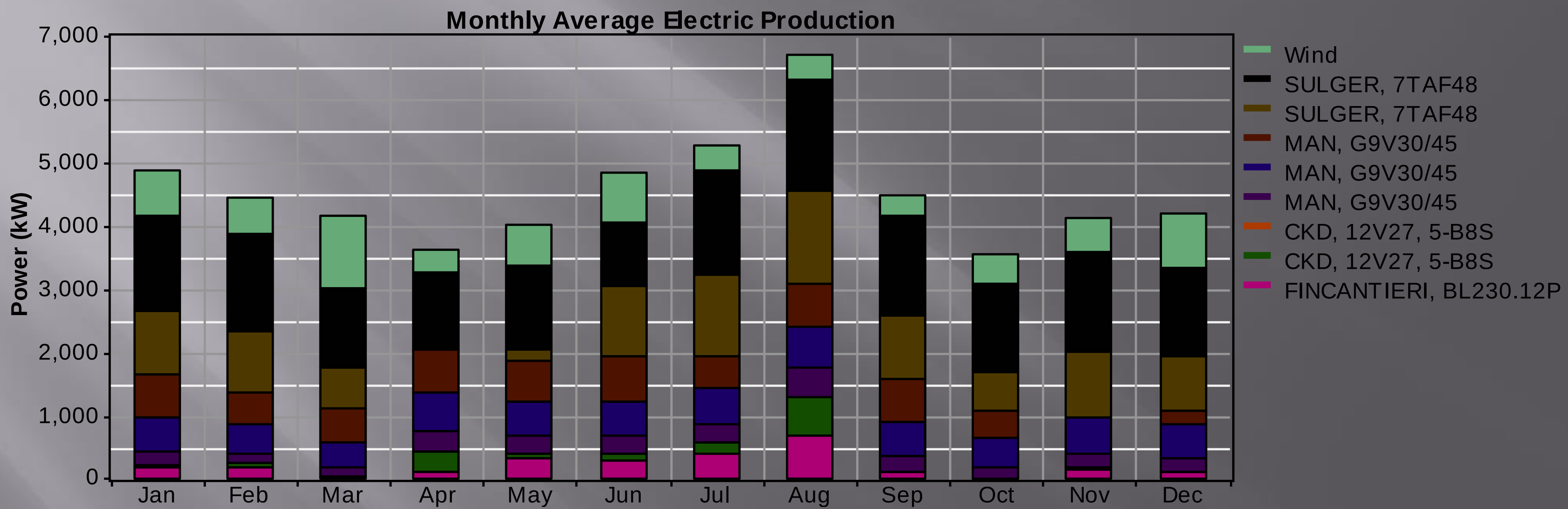
- 3 Wind Turbines

2 Vestas V – 44 (0,6 MW each)

1 Vestas V – 52 (0,85 MW)

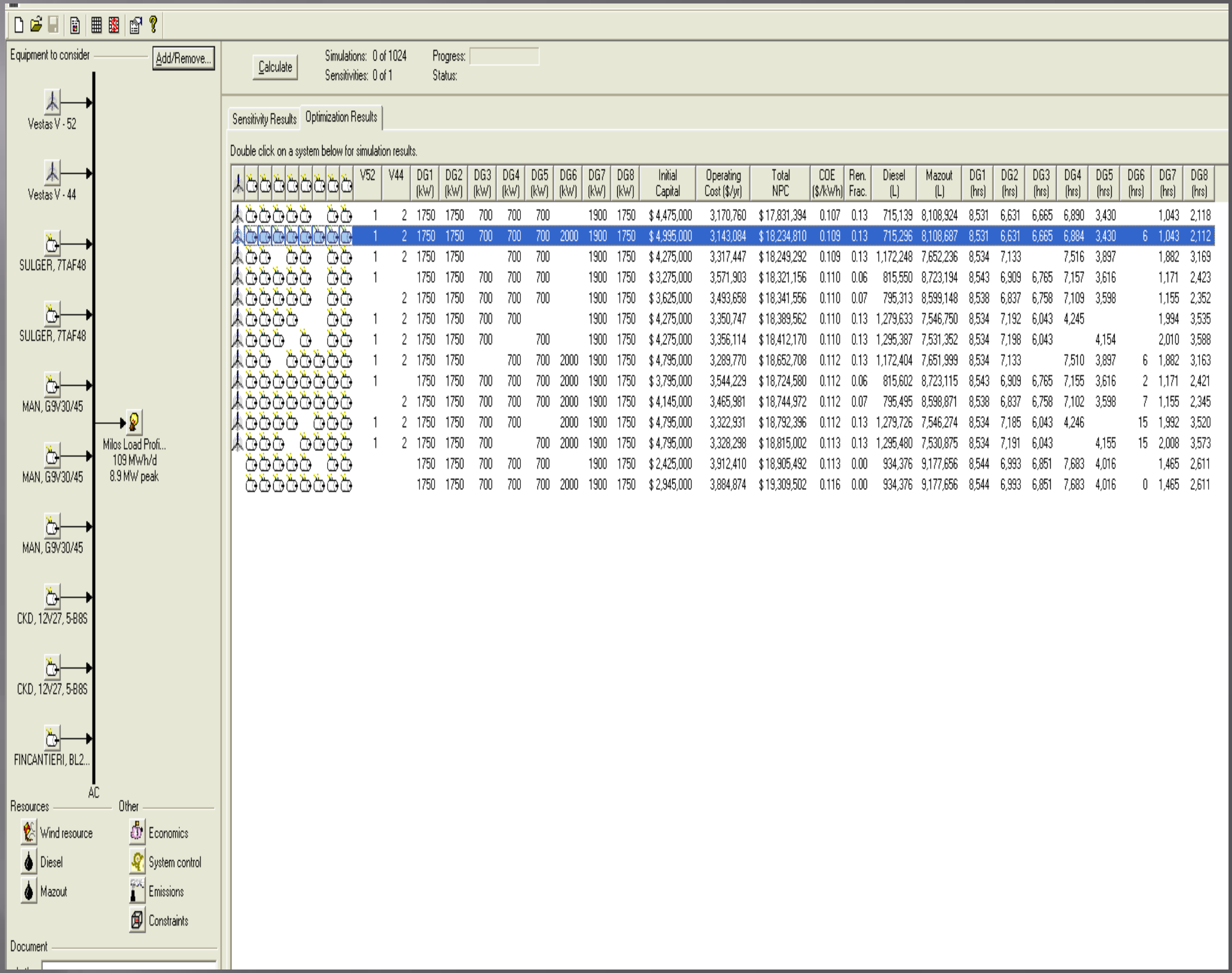
Basic Inputs
Heavy Oil Price: 0,34 €/L
Diesel Price: 0,68 €/L
Generators Capital Cost: 250 – 300 €/kW
Wind Turbines Capital Cost: 1.000 €/kW
Project Lifetime: 5 years

MILOS SIMULATION RESULTS
Existing power system



MILOS SIMULATION RESULTS
Existing power system

- Levelized COE: 113 €/MWh
- Wind Turbines Power Production: 5,3 GWh/yr
- Renewable Fraction: 0,134
- Diesel: 715.296 L
- Heavy Oil: 3.054.864 L



V52	V44	DG1 (kW)	DG2 (kW)	DG3 (kW)	DG4 (kW)	DG5 (kW)	DG6 (kW)	DG7 (kW)	DG8 (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Mazout (L)	DG1 (hrs)	DG2 (hrs)	DG3 (hrs)	DG4 (hrs)	DG5 (hrs)	DG6 (hrs)	DG7 (hrs)	DG8 (hrs)
1	2	1750	1750	700	700	700		1900	1750	$ 4,475,000	3,170,760	$ 17,831,394	0.107	0.13	715,139	8,108,924	8,531	6,631	6,665	6,890	3,430		1,043	2,118
1	2	1750	1750	700	700	700	2000	1900	1750	$ 4,995,000	3,143,084	$ 18,234,810	0.109	0.13	715,296	8,108,687	8,531	6,631	6,665	6,884	3,430	6	1,043	2,112
1	2	1750	1750		700	700		1900	1750	$ 4,275,000	3,317,447	$ 18,249,292	0.109	0.13	1,172,248	7,652,236	8,534	7,133		7,516	3,897		1,882	3,169
1		1750	1750	700	700	700		1900	1750	$ 3,275,000	3,571,903	$ 18,321,156	0.110	0.06	815,550	8,723,194	8,543	6,909	6,765	7,157	3,616		1,171	2,423
	2	1750	1750	700	700	700		1900	1750	$ 3,625,000	3,493,658	$ 18,341,556	0.110	0.07	795,313	8,599,148	8,538	6,837	6,758	7,109	3,598		1,155	2,352
1	2	1750	1750	700	700			1900	1750	$ 4,275,000	3,350,747	$ 18,389,562	0.110	0.13	1,279,633	7,546,750	8,534	7,192	6,043	4,245			1,994	3,535
1	2	1750	1750	700		700		1900	1750	$ 4,275,000	3,356,114	$ 18,412,170	0.110	0.13	1,295,387	7,531,352	8,534	7,198	6,043		4,154		2,010	3,588
1	2	1750	1750		700	700	2000	1900	1750	$ 4,795,000	3,289,770	$ 18,652,708	0.112	0.13	1,172,404	7,651,999	8,534	7,133		7,510	3,897	6	1,882	3,163
1		1750	1750	700	700	700	2000	1900	1750	$ 3,795,000	3,544,229	$ 18,724,580	0.112	0.06	815,602	8,723,115	8,543	6,909	6,765	7,155	3,616	2	1,171	2,421
	2	1750	1750	700	700	700	2000	1900	1750	$ 4,145,000	3,465,981	$ 18,744,972	0.112	0.07	795,495	8,598,871	8,538	6,837	6,758	7,102	3,598	7	1,155	2,345
1	2	1750	1750	700	700		2000	1900	1750	$ 4,795,000	3,322,931	$ 18,792,396	0.112	0.13	1,279,726	7,546,274	8,534	7,185	6,043	4,246		15	1,992	3,520
1	2	1750	1750	700		700	2000	1900	1750	$ 4,795,000	3,328,298	$ 18,815,002	0.113	0.13	1,295,480	7,530,875	8,534	7,191	6,043		4,155	15	2,008	3,573
		1750	1750	700	700	700		1900	1750	$ 2,425,000	3,912,410	$ 18,905,492	0.113	0.00	934,376	9,177,656	8,544	6,993	6,851	7,683	4,016		1,465	2,611
		1750	1750	700	700	700	2000	1900	1750	$ 2,945,000	3,884,874	$ 19,309,502	0.116	0.00	934,376	9,177,656	8,544	6,993	6,851	7,683	4,016	0	1,465	2,611

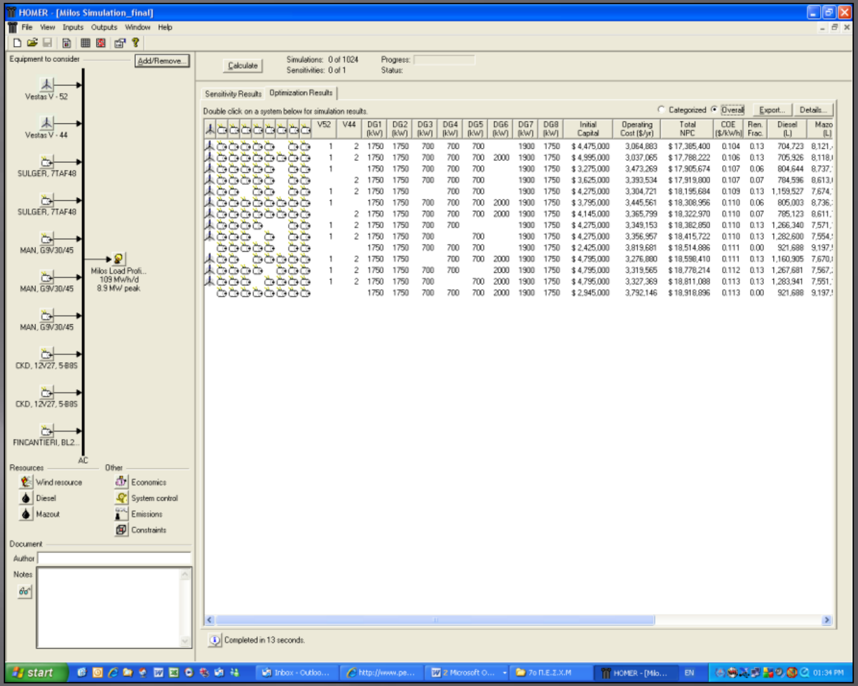
The proposed RES & hydrogen-based power system for Milos island

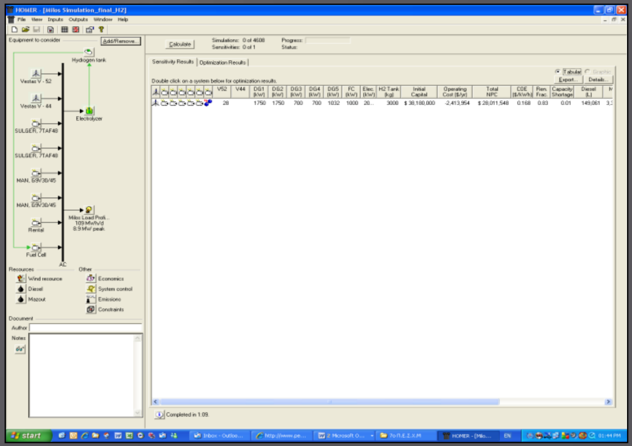
According to the simulation results, the components of the optimum RES & hydrogen-based power system when hydrogen is introduced as energy storage medium in the power system are depicted in the following Table

Component	Type	Number	Size
Wind Turbine	V-52	28	**850 kW (each)**
	V-44	2	**600 kW (each)**
Thermal Generator	Sulger	2	**1750 kW (each)**
	Man	2	**700 kW (each)**
	Rental	1	**1032 kW**
Fuel Cell	PEM	1	**1 MW**
Electrolyser	Alkaline	1	**2 MW**
Hydrogen Compressor	**Metal Hydride**	**1**	Up to 400 Nm3/h
Hydrogen storage tank	**Compressed gas**	**1**	**4000 kg**

Architecture of the proposed power system

- Levelized COE: 112 €/MWh
- Wind Turbines Power Production: 32 GWh/y
- Renewable Fraction: 0,925
- Diesel: 154.905 L
- Heavy Oil: 8.108.687 L





Financial analysis

Technology	Type	Unit Cost	Initial Cost	Replacement Cost
Wind Turbine	V-52	1,200 €/kW	19,992,000 €	0 €
	V-44	1,200 €/kW	1,008,000 €	0 €
Thermal Generator	Sulger	251 €/kW	880,000 €	88,000 €
	Man	286 €/kW	400,000 €	40,000 €
	Rental	145 €/kW	150,000 €	0 €
Fuel Cell	PEM	3,000 €/kW	1,500,000 €	450,000 €
Electrolyser + Hydrogen Compressor	Alkaline + Metal Hydride	2,000 €/kW	2,000,000 €	0 €
Hydrogen storage tank	Compressed gas	800 €/kg	1,600,000 €	0 €
Total			27,530,000 €	

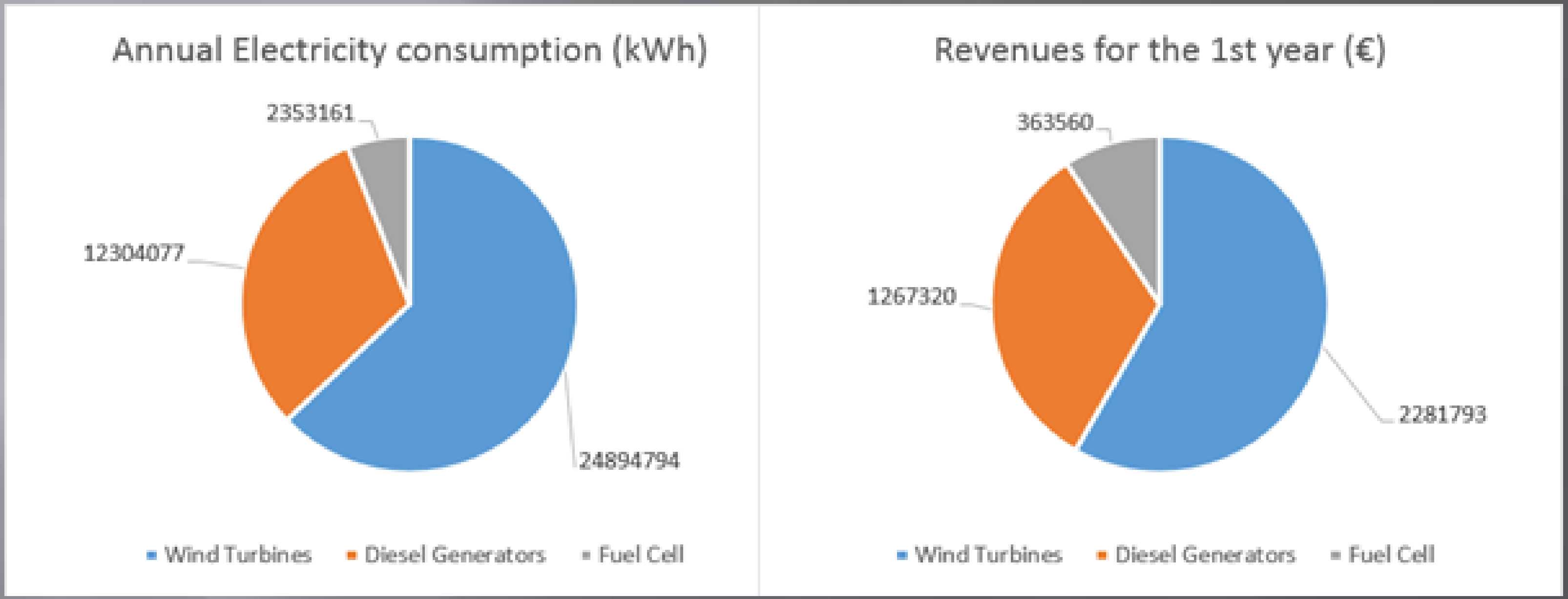
investment costs of the proposed RES & hydrogen-based power system

Financial analysis

Parameter	Type	Unit Cost	Operational Cost
Wind Turbine	V-52	17,340 €/year	**485,520 €/year**
	V-44	12,240 €/year	**24,480 €/year**
Thermal Generator	Sulger	6.5 €/hour	**44,948 €/year**
	Man	5.5 €/hour	**36,636 €/year**
	Rental	5.5 €/hour	**5,478 €/year**
Fuel Cell	PEM	1.02 €/hour	**4,418 €/year**
Electrolyser + Hydrogen Compressor	Alkaline + Metal Hydride	50,000 €/year	**50,000 €/year**
Hydrogen storage tank	Compressed gas	4,000 €/year	**4,000 €/year**
Fuel	Diesel	0.68 €/L	**105,336 €/year**
	Heavy oil	0.34 €/L	**1,038,654 €/year**
Emissions	CO_2	21 €/t	**206,677 €/year**
Total			**2,006,147 €/year**

operational costs of the proposed RES & hydrogen-based power system

Annual electricity consumption and revenues for the 1st year of the RES & Hydrogen-based power system



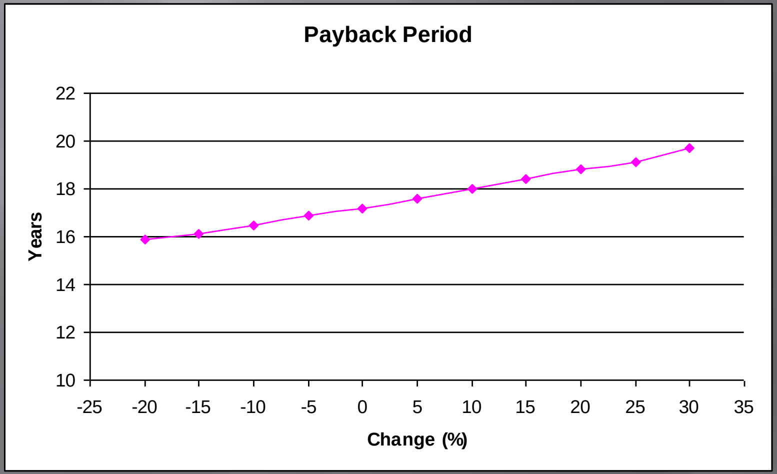
Environmental and Social Impacts

Milos proposed power system	
Avoided Emission values	
NOx	**317,722 kg/year**
SO_2	**328,536 kg/year**
PM_{10}	**2,684 kg/year**
CO_2	**17,120,117 kg/year**
Assumptions	
Mortality value	**75,000 €/Life Year Lost**
Abatement cost per tonne of CO_2	**19 €/t**
Summary Results	
Human Health Mortality	**629,000 €/year**
Human Health Morbidity	**332,000 €/year**
Crops	**293,000 €/year**
Materials	**44,500 €/year**
CO_2	**325,000 €/year**
Total External Benefit	**1,623,500 €/year**
PV of total external benefit	**18,621,417 €**

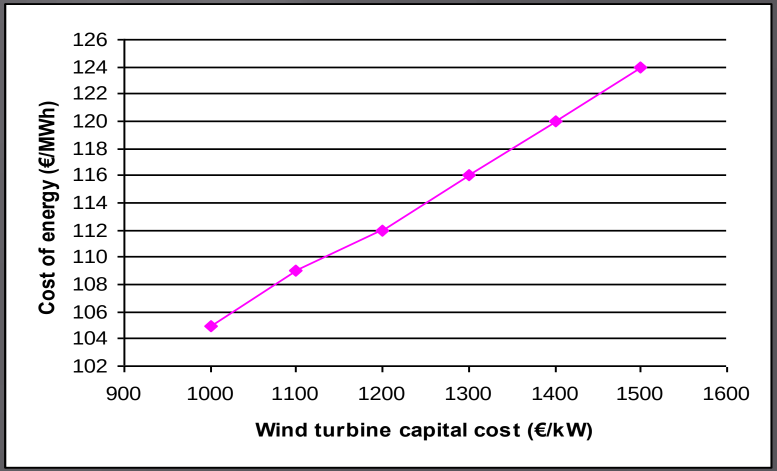
Avoided emissions due to the proposed RES & Hydrogen power system in Milos island

Sensitivity analysis

Parameter	Min.	Original	Max.
Wind turbine capital cost	1000 €/kW	1200 €/kW	**1500 €/kW**
Fuel Cell capital cost	2000 €/kW	3000 €/kW	**3000 €/kW**
Electrolyser + Compressor capital cost	1500 €/kW	2000 €/kW	**2000 €/kW**
Diesel price	-20%	0.68 €/L	**+30%**
Heavy oil price	-20%	0.34 €/L	**+30%**
CO_2 emission trading allowance	-30%	21 €/t	**+5%**
Fuel cell electricity price	**-20%**	**0.15 €/kWh**	**+20%**



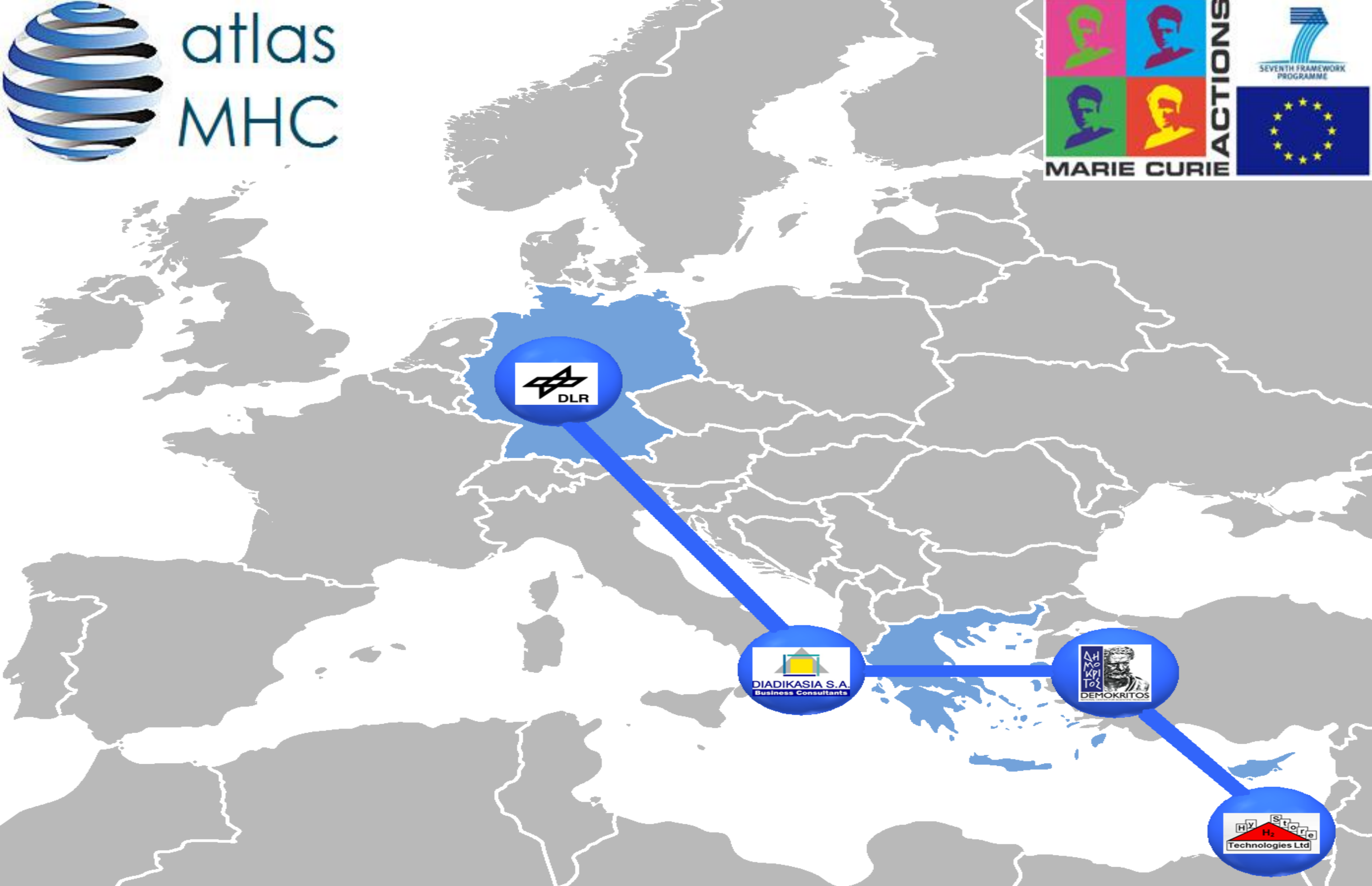
Impact of heavy oil price on Payback Period



Impact of wind turbine capital cost on cost of energy

Conclusions

- Very good commercialization potential for MH2C
- Both major target markets identified (i.e. Large – scale Hydrogen Production using excess energy from RES and H2 vehicle refueling stations), show a rapid development.
- The cost of hydrogen compressors does not have a significant impact on the technoeconomic analysis of large-scale RES – Hydrogen power systems
- A cost reduction in the order of 15-20% to the currently existing cost of the thermal compressor would play a significant role in the commercialization of the product in small scale applications, such autonomous, self sufficient residences



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http://www2.ipta.demokritos.gr/atlas-mhc/