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Magneto-caloric machine for power generation

Market opportunities and potential analysis

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Preamble

The current study is based on some decisive assumptions that will be summed up here.

The selection of the business cases was made based on the properties of the magneto-caloric material gadolinium. The Curie-temperature of Gadolinium is approximately 19.3°C. Therefore, industries disposing of cold water are sought. Currently, materials whose Curie point can be set over a large temperature range exist for magneto-caloric cooling technology (e.g. materials from BASF, VAC). However, these materials were optimized for other applications than MCM and must therefore be developed further before an efficient use for the engine becomes possible. However, it can be assumed that the restriction of a cold water source by the material properties may disappear in the future, so as to only leave the ΔT between both fluids as a decisive factor (10 and 30°C would be equivalent to 60 and 80°C). The profitability calculations are based on future materials capable of exploiting the complete temperature difference (use over several cascades).

Until now, to our best knowledge, the demonstrator built by the Swiss Blue Energy AG is the only magneto-caloric machine of this type with a power in the kW range. Heiniger et al. (2012) balanced this machine, which displayed a thermal overall efficiency of 0.75% (>1,5 % in the part-load operational range), which corresponds to approx. 10% of the Carnot efficiency. This demonstrator was designed and built purely for illustrative purposes and without a focus on efficiency. In a SFOE supported study by Kitanovski et al. (2008a), magneto-caloric machines for power generation were analysed and economically evaluated. In the following study, the calculation of the thermal MCM efficiency is based on results from Kitanovski et al. (2008a), or Vuarnoz et al. (2012), showing that 40% of the Carnot efficiency can be used (Temperatures < 100°C, 2 Tesla magnetic flux density, 30% volume component).

1 Starting situation

Magneto-caloric machines (MCM) are capable of generating rotational energy using small temperature differences between two fluids (<100°C), which can then be used to produce electricity. This young technology thereby provides the possibility of generating electricity from unused waste heat. In particular, the temperature difference and not the temperature level are determining for the power of the MCM. This makes this technology usable in the currently (almost) unusable low temperature waste heat domain.

The Swiss Blue Energy AG (SBE) developed a machine which uses the characteristics listed above for electricity production (further information available on www.swiss-blue-energy.ch). The Swiss Federal Office of Energy (SFOE) supports two parallel research projects about this machine. Aside from the present study, a research project at the institute for thermo- and fluid-engineering (ITFE) of the school of engineering of the FHNW was supported. The aim of this project was to develop an industry-ready prototype based on the demonstrator designed by SBE which would be capable of withstanding a continuous industrial test. Tight cooperation with this research group allowed the determination of the technical parameters as starting point of the profitability analysis.

The stakeholders are numerous when it comes to energy questions. While from an business perspective, the electricity supply, operational safety and economic aspects are in focus, the national economy does not only focus on economic aspects, but also increasingly ecological aspects and other factors require consideration. In our analysis, we will focus on the business aspects only.

The study exclusively analyses waste heat sources that occur due to industrial production processes. Further possible use domains, such as for example in combination with solar energy or geothermal energy are not part of the contract and are therefore deliberately not treated. Kitanovski et al. (2008a) already showed that magnetic energy generation technologies would have the greatest market opportunities in the use of industrial waste heat.

The study limits itself to industrial solutions with waste heat in the form of water. In the future, it is quite possible that waste heat from other fluids or aggregate states may be used, extending the range of applications.

The results of the profitability analysis listed below are based on several assumptions and estimations, mainly for the properties of a future MCM. One of these assumptions for example contains a fundamental innovation in magneto-caloric material science. As soon as the technical development of the material and the construction are complete, the following values should be verified and adjusted to the new circumstances if needed.

2 Objectives

The profitability of the MCM for Switzerland and Germany is estimated in the scope of the research project "Profitability analysis - magneto-caloric machine (MCM)" supported by the SFOE and SBE. The present study aims to determine the profitability of the MCM in the industrial sector as well as the market opportunities for Switzerland and Germany and to create a requirements specification for the industry.

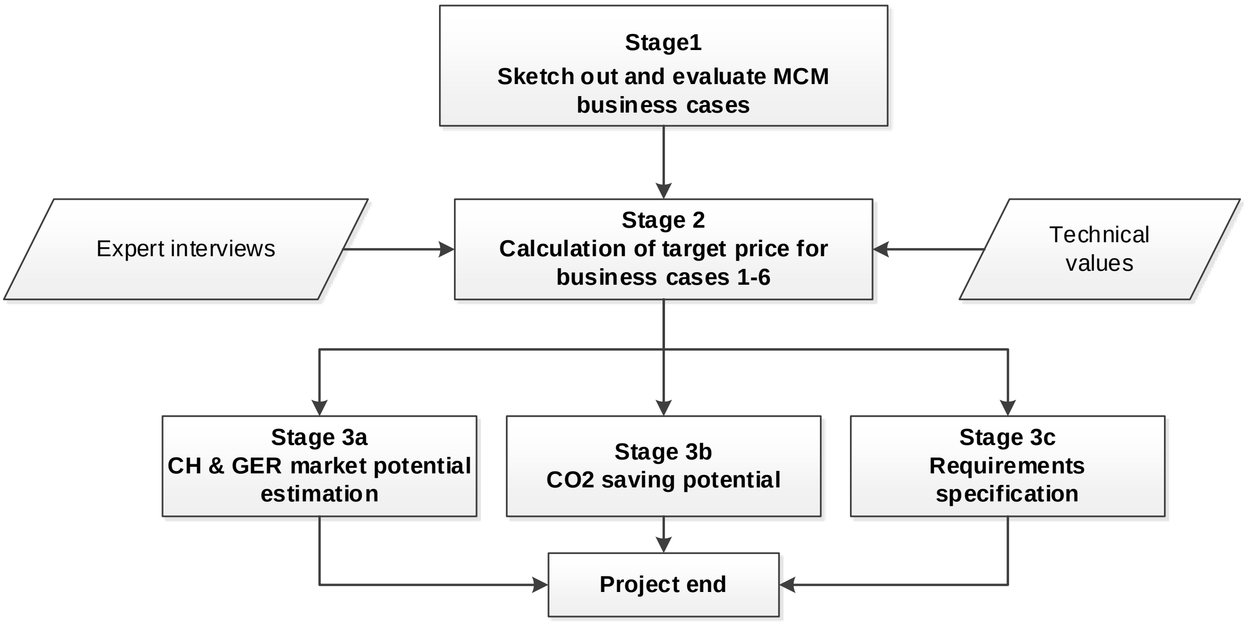
The following question for the MCM for electricity generation needs to be explicitly answered in the scope of this study:

- The target price for different sizes of installation types is validly investigated.
- The requirements specification for the MCM is defined for the target group "industrial waste heat generators".
- The market attractiveness of MCM technologies in the industrial domain is clarified.
- The market potential of MCM installations is known for Switzerland and Germany (number of installations/kW).
- The CO_2 saving potential from MCM installations for electricity generation in the industrial waste heat market of Switzerland is defined.

3 Approach / Method

A three-step procedure was selected to reach the objectives. In the first step, potential business cases are sketched out and evaluated by expert interviews. Using the input data from the technical side and the data values gathered from expert interviews, two market segments were identified and the most promising business cases were selected for each segment. During the second stage, the profitability of an actual installation was calculated for each business case using the net present value method. The results obtained from stage 2 allow for generation of the market opportunities, the CO2 saving potential and the requirements specification for Switzerland and Germany.

Figure 1: Profitability analysis procedure concept



Method

Six business cases were selected from the potential industries for the estimation of the market opportunities. The target price was calculated for different sized installation types due to the business cases. The dynamic investment cost calculation was selected as calculation method. A slight modification of the net present value method (see appendix 12) provides the target price. The target price is the maximum accepted market price for an MCM. This price should contain a profit margin aimed for by the manufacturer along with the production and installation costs. Operational, technical and economic factors are considered in the calculation (see section 12.1.3).

The target price is based on estimations of the technical properties of future MCEs. These estimations were based on measurements on the demonstrator (Heiniger et al, 2012) and stem from current research reports (Kitanovski et al., 2008, Vuarnoz et al., 2012). One of the most important assumptions on the technical side is the existence of a material that fulfils the assumed efficiency factor and whose Curie point can be set over a large temperature range. Current and future production costs of an installation have no influence on the target price. The target price starts at the client side and provides an orientation value for the maximum accepted final market price.

4 Identification of business cases

4.1 Industries with waste heat potential

Since no data for waste heat are available for Switzerland, we take the energy intensity on industry level as an indicator. In order to obtain the required amount of waste heat, the energy consumption per production site is calculated. This indicator clearly shows that the chemistry/pharmaceutical industry, cement/concrete production and metal/steel production industries have the greatest potential. The next-largest potential lies in food production. This potential may actually be larger than shown by the indicator, as the industry itself is very heterogeneous when it comes to plant size. It is therefore plausible that a non-negligible number of very large waste heat producers exist in the food production industry.

Table 1: Energy consumption and structure of the relevant industries 2012 - Switzerland. Source: SFOE

Energy statistics 2012	Total TJ	Production sites (PS)	FTE	TJ/PS	GWh/PS
Cement / Concrete:	13'941	38	1'595	366.87	101.91
Metal / Steel:	7'496	124	7'563	60.45	16.80
Chemistry / Pharmaceutical:	32'198	822	59'202	39.17	10.88
Food:	17'070	2'521	54'389	6.77	1.88
Paper / Printing:	12'985	2'524	29'941	5.14	1.43
Metal devices:	15'758	10'174	200'872	1.55	0.43

4.2 Industries with cold water potential

Also, no official statistics for the industrial use of water are available. Data is partially available locally and for the cantons, but are not publicly accessible. Geographic indications of retrieval and return rights of source and surface water are partially visible in the online GIS browsers of the cantons, however this is without effective usage data (e.g. Zurich: www.gis.zh.ch).

Based on our knowledge, the newest and only statistic for water use by the industry comes from 2009, written by the Swiss Association for Gas and Water (SVGW). The data relate to the operating year 2006. Not all industry branches are recorded in the statistics, the relevant water users can however be representatively displayed.

The SVGW statistics (2009) clearly show that the largest users are nuclear power plants, followed by the industrial sector (see Figure 2). Relevant industries for water use are the chemical, waste, paper, metal and food industries (see Figure 3). How much of this water can be used as waste heat or cold sources is not visible from this data and had to be clarified individually.

Figure 2: Total overview of the water consumption for Switzerland in 2006. Source: SVGW (2009)

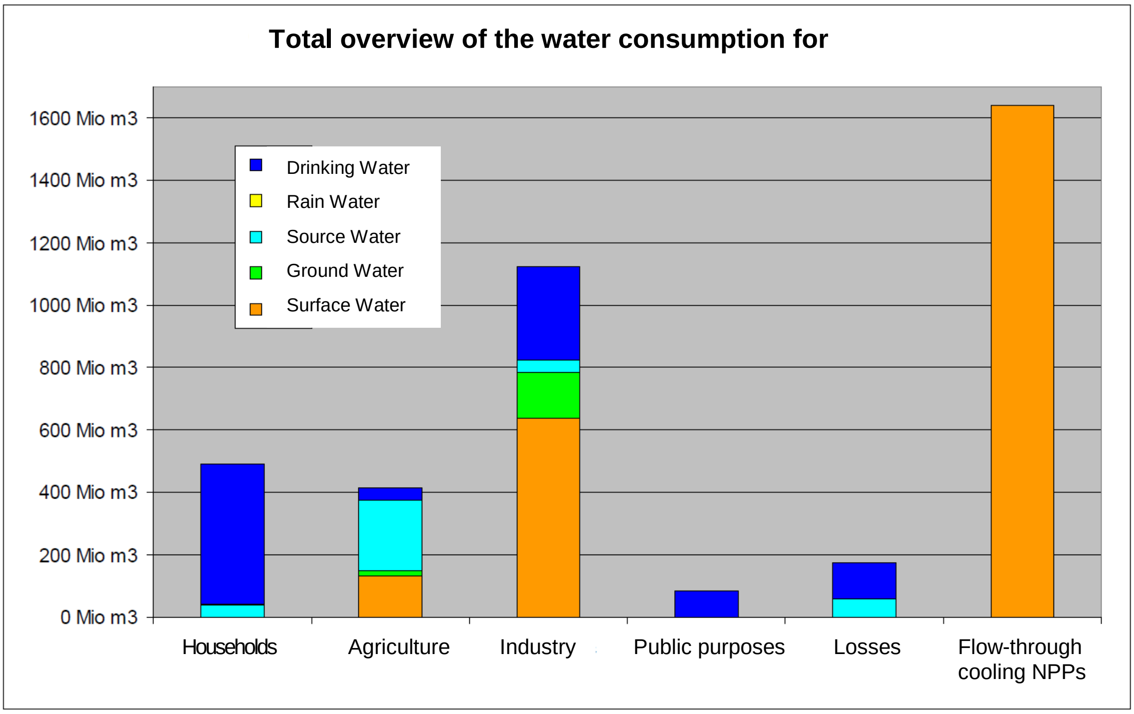
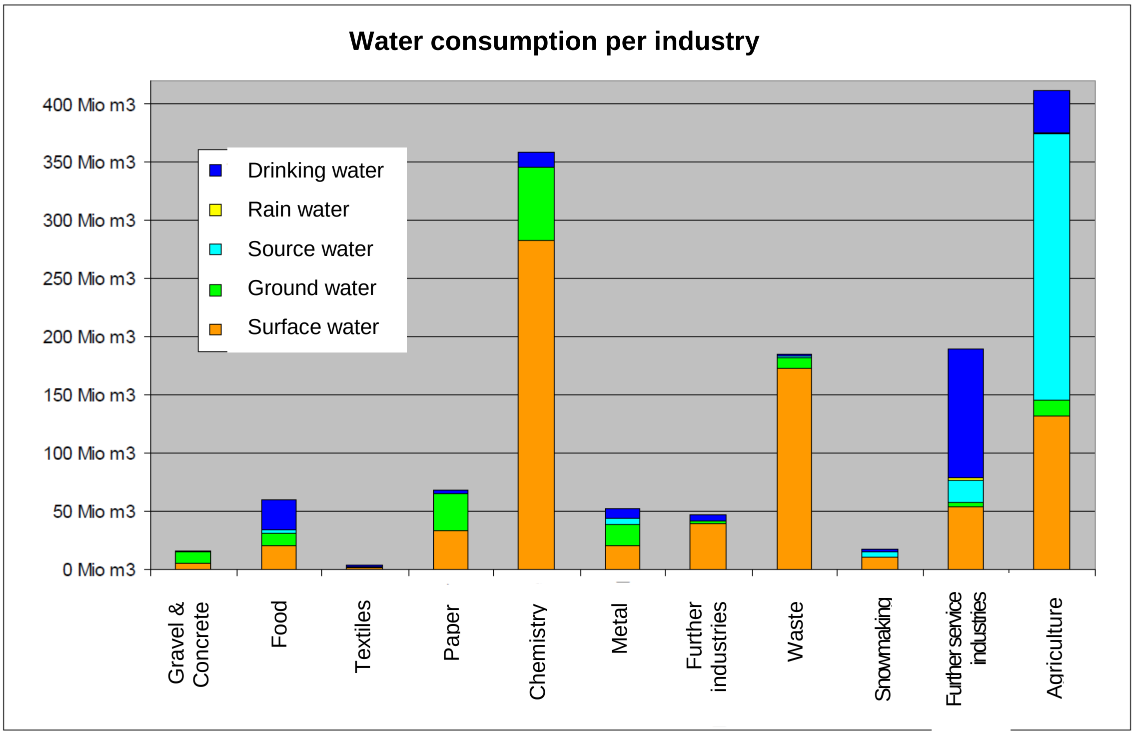


Figure 3: Water consumption per industry in 2006. Source: SVGW (2009)



4.3 Industries with waste heat and cold water potential

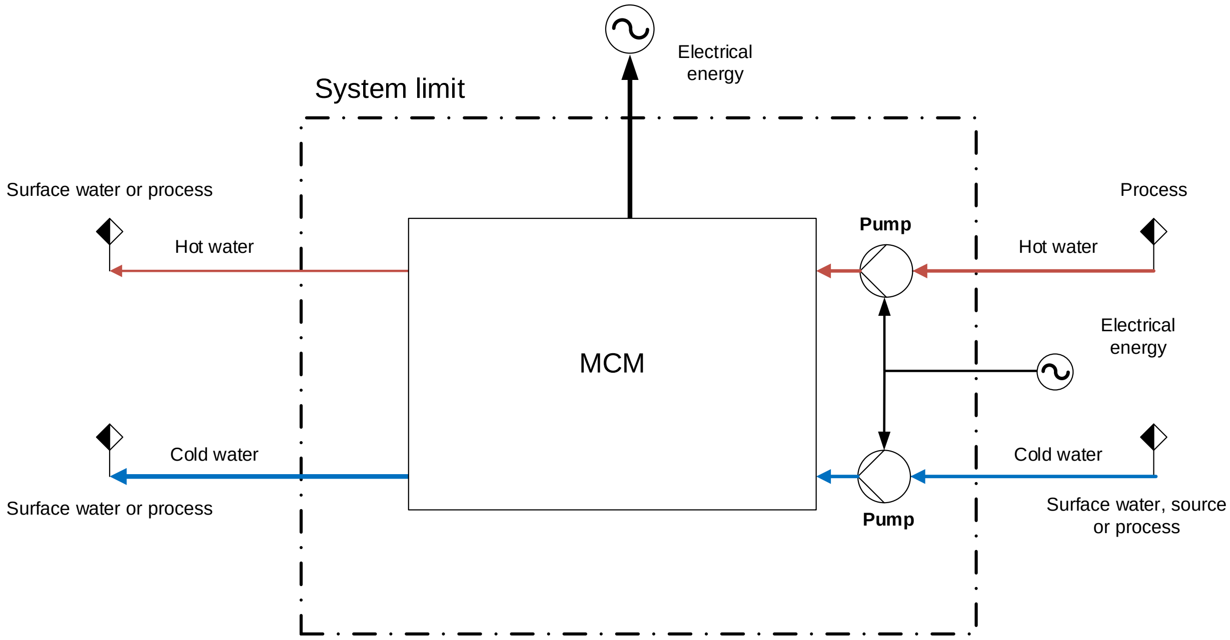
From this analysis, we conclude that the branches of chemical, metal, paper and food industry could be potential sites for an MCM. Aside from the paper industry, partners for relevant business cases were found in all industry branches. However, the production processes within the branches are very heterogeneous, making generalization of the results complicated. Additionally, the cement and concrete industry were investigated due to the high energy requirements per working site and the relatively standardized production process.

5 Business cases

The integration potential for an MCM in existing processes was precisely discussed with energy and/or environment managers in the participating companies. There was always a great readiness for making data available.

The basic assumption of the cases is a black box, in which the temperature difference is optimally used (including cascading). The target price relates to a completely installed machine. The inputs required are hot and cold water as well as electrical energy for the pumps, the output results in electrical energy as well as two mass flows (hot and cold).

Figure 4: MCM system limit



The study by Vuarnoz et al. (2012) evaluates magneto-caloric engines and models the total efficiency to 40% of the Carnot efficiency for a magnetic field of 2 Tesla (losses included). According to our best knowledge, this study is the most up to date to have conducted such simulations. We therefore take a total thermal efficiency at 40% of the Carnot efficiency for the business cases.

Other assumptions are:

- Capital costs: 8%
- Duration of use: 15 years
- Pressure losses within the MCM: 1 bar

All other parameters are real values from the companies, e.g. the operating hours, electricity costs (both actual energy costs for the companies and output of the MCM), mass flows, water costs, etc. Table 2 sums up the input data and the results of the business cases.

The basis for the profitability analysis is a modification of the dynamic net present value investment cost calculation. The method is described in detail in section 12. The resulting target price covers all costs, including the margin for the manufacturer (Production, sales, installation, marketing, etc.).

The following business cases stem from the metal/steel, energy production, food, cement and chemical/pharmaceutical industries. All cases were made with Swiss companies. The market segments are divided according to available mass flows. If more than 50m3/h of hot and cold water respectively are available, the company is classified as a large waste heat producer.

5.1 Submarket: Large waste heat producers

Table 2: Business cases in submarket of large waste heat producers

		Unit	Case 1	Case 2	Case 3	Case 4	Case 5
Volume	WW	m^3/h	900	60	130	130	60
	CW	m^3/h	900	60	130	130	60
Temperature	WW	°C	36.5	57	60	60	28
	CW	°C	10	17	25	30	6
Price / Costs	WW	CHF/m^3	0.00	0.00	0.00	0.00	0.00
	CW	CHF/m^3	0.003	0.00	0.00	0.018[1]	0.00
	Elect ricity	CHF/kWh	0.12	0.10	0.10	0.10	0.11
Operating hours[2]		h/a	8'760	7'500	7'000	7'000	8'760
Altitude difference	WW	m	0	0	0	0	3
	CW	m	5[3]	5	5	3	40
Cost saving compared to current situation		CHF/a	26'000	0	0	0	750[4]
Thermal efficiency[5]			3.4%	4.9%	10.5%	9.0%	3.0%
MCM power		kW	949	135	222	163	45
Pump power		kW	89	6	13	35[6]	12
MCM net power		**kW**	**860**	**129**	**209**	**128**	**33**
Net production		MWh/a	7'500	970	1'500	900	280
Target price / kW		**CHF/kW**	**8'100**	**6'100**	**5'600**	**4'500**	**6'000**
Target price / kWh		**Rp/kWh**	**6.8**	**5.7**	**5.6**	**5.5**	**6.4**
Target price total		**CHF**	**7'690'000[7]**	**830'000[8]**	**1'250'000**	**740'000[9]**	**270'000**
CO2 saving potential		t CO2eq[10]	920	120	180	110	35

1 Case 4 has no cold water access, which is why a distinct cooling circuit is required for the MCM. The water costs are calculated based on the energy usage of the cooling tower (motor power for water distribution system and axial ventilator 23kW, Cofely EWK cooling tower (Cofely 2013)). Is directly calculated as cost in the total pump power of the machine.

2 Number of hours during which waste heat is available. Depending on the maintenance interval of the MCM, the operating hours of the MCM are reduced.

3 Saving pump energy, since no additional water needs to be pumped for mxing before returning the water back to the water source.

4 Cost saving through reduced energy return to the water.

5 40% of the Carnot efficiency. See Kitanovski et al. (2008a).

6 Including motor power for cooling tower (water distribution system and axial ventilator).

7 The target price should cover the cost of a water filter along with the MCM since the cold water source contains sand.

8 Since the waste heat source has a relatively large component of solid materials, a heat exchanger needs to be used to obtain the waste heat, which should also be covered by the target price.

9 The target price should cover the cost of a distinct cooling circuit along with the costs of the MCM.

10 We use the CO2 emissions of the Swiss supplier electricity mix of 122 g CO2eq/kWh for calculations. Source: FOEN (2014).

The target price in the market segment of large waste heat producers lies between 4'500 and 8'100 CHF per kW installed power. Depending on the production process, this price should cover the costs of a heat exchanger or water cooling tower, additionally to the total costs of a completely installed MCM. This price level could possibly be reached in a small series production using the appropriate materials. The target price per kW may not be compared one-to-one between the cases. For example, case 2 and case 5 have an (almost) identical Target Price / kW, however the target prices for the complete installation massively differ from one another. The share of fixed manufacturing and material costs (Generator, etc.) per kW is significantly higher for small installations when compared to larger ones. Therefore, the target price for small installations leaves less scope for power-dependent production costs and margin.

As soon as a resource (hot or cold water) gets charged, the target price (of the complete installation) drops to a very low level (see case 3). Causes for water to be charged are for example:

- Fees (from regulation)
- Non-availability of surface or ground water. Additionally, a cooling tower must be operated, whose operating costs make the water costly. (Furthermore the investment costs of the cooling tower need to be additionally covered by the target price).
- Water needs to be pumped (over a large height difference).

A positive effect on the target price is obtained from the mass flow, the ΔT, electricity price (revenue) and the operating hours. Further analysis of the different factors may be found in section 6.

5.2 Submarket: Small waste heat producers

Table 3: Business cases in submarket of small waste heat producers

		Unit	**Case 6**	**Case 7**
Volume	WW	m3/h	25	10
	CW	m3/h	25	10
Temperature	WW	°C	40	60
	CW	°C	15	13
Price / Costs	WW	CHF/m3	0	0
	CW	CHF/m3	0	0
	Electricity	CHF/kWh	0.12	0.10
Operating hours		h/a	7'600	8'400
Altitude difference	WW	m	0	0
	CW	m	0	0
Cost saving compared to current situation		CHF/a	0	0
Thermal efficiency			8%	14%
MCM power	kW		23	31
Pump power	kW		2	1
MCM net power	**kW**		**21**	**30**
Net production	MWh/a		160	250
Target price / kW	**CHF/kW**		**7'100**	**7'000**
Target price / kWh	**Rp/kWh**		**6.6**	**5.8**
Target price total	**CHF**		**160'000**	**220'000**
CO2 saving potential	t CO2eq[11]		20	30

The target prices per kW in this submarket are on a level similar to the other submarket. However, the price of the complete installations is relatively low. This also shows the problematic of this submarket. The required fixed material costs (e.g. generator) should be kept very low in order to reach the target price.

More waste heat would be available in both of the studied cases. The MCM potential is much smaller than the effective waste heat potential of the companies due to limited water availability or the decentralized availability of waste heat on the production site.

11 We calculate using the CO2 emissions of the Swiss supplier electricity mix of 122 g CO2eq/kWh. Source: FOEN (2014).

6 Sensitivity analysis of the target price

In order to better understand the relevance of the different input values on the target price, a sensitivity analysis was conducted in this section. In the first part, the input values are analysed by themselves with absolute values, in the second part, a standardized comparison between the input values is made.

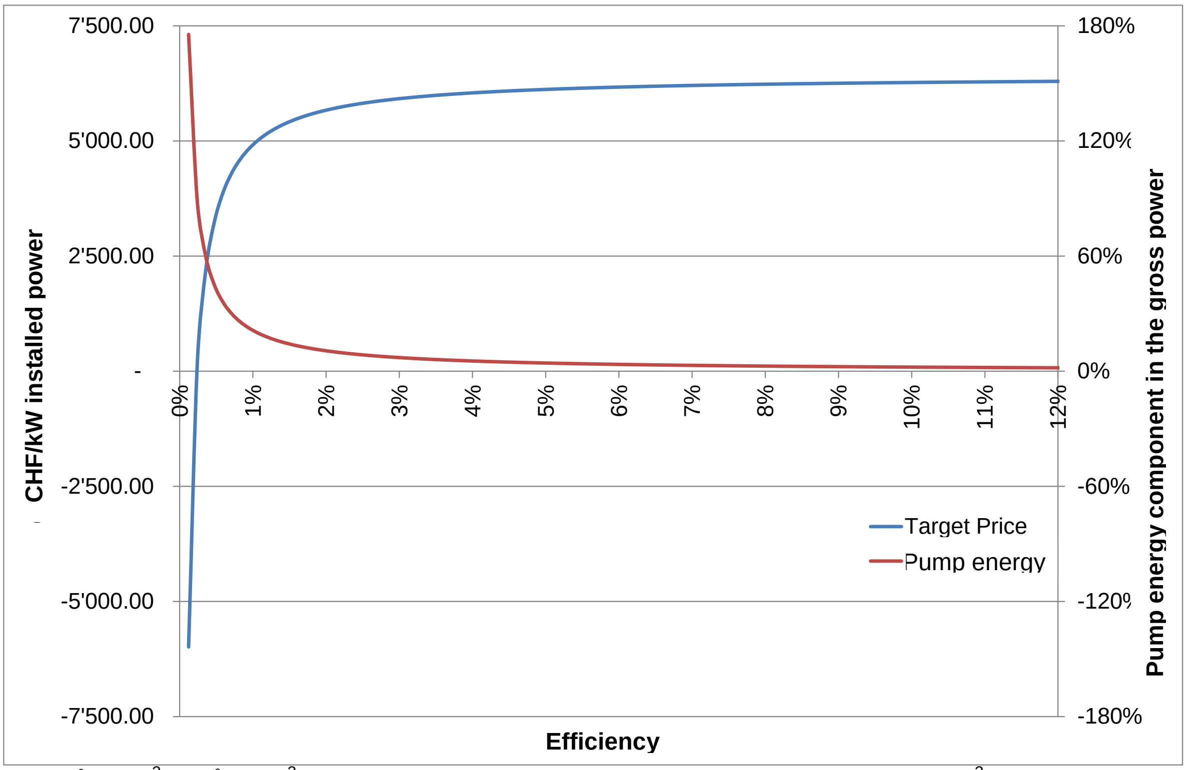
6.1 Sensitivity of influencing factors

The target price per kW of installed power stagnates starting from a certain value on for those influence factors that have a direct effect on the power of the machine. Figure 4 shows that this stagnation is due to the required pump energy. If the efficiency rises above approx. 2%, the share of pump energy of the gross power stagnates. I.e. revenues and costs grow proportionally to each additional unit of power, so that the price per kW stagnates. According to figure 4, it is essential for the profitability of the MCM that the efficiency comes in the flat area of the curve, i.e. that it is larger than approx. 1.5-2%.

Considering the temperature difference, the machine is in the optimal range as soon as ΔT is larger than approx. 20°C (see figure 5). Since the revenues and costs are linearly dependant on the mass flow, the target price per kW is independent of the mass flow and stagnates at the level of 6'100 CHF/kW.

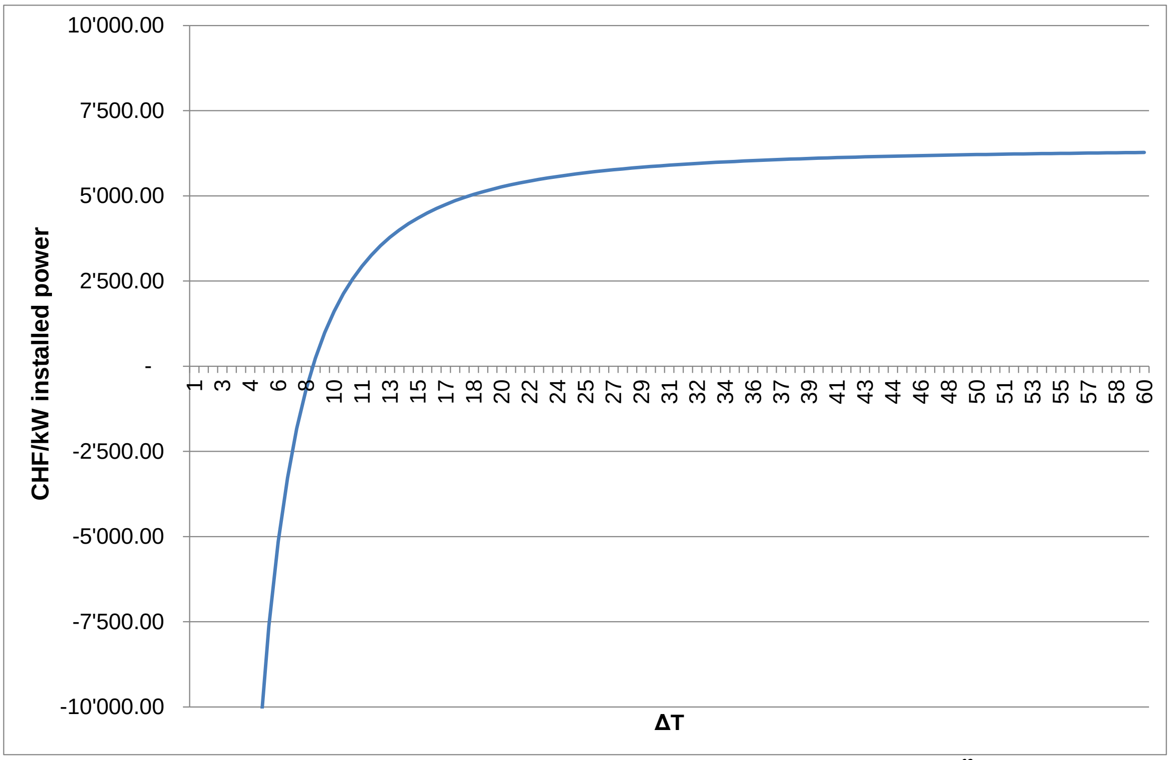
Operational and economic influence factors have a more or less linear effect on the target price. Here, the comparison between factors is most interesting, and is dealt with in the next section. Sensitivity diagrams for the individual factors with absolute values may be found in section 13.

Figure 5: Target price and pump energy depending on the efficiency.



Note: $\mathring{m}_H$=60m³/h, $\mathring{m}_C$=60m³/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh, P_{Water}=0.00CHF/m³, i=8%, T=15 Years, $Operating\ hours = 7'500 h/a$.

Figure 6: Target price depending on the temperature difference.



Note: $\mathring{m}_H$=60m^3/h, $\mathring{m}_C$=60m^3/h, P_{el}=0.10CHF/kWh, P_{Water}=0.00CHF/m^3, i=8%, T=15 Years, $^{\eta_{th}}/_{\eta_{carnot}} = 40\%$, $Operating\ hours = 7'500h/a$.

6.2 Conclusions of sensitivity analysis

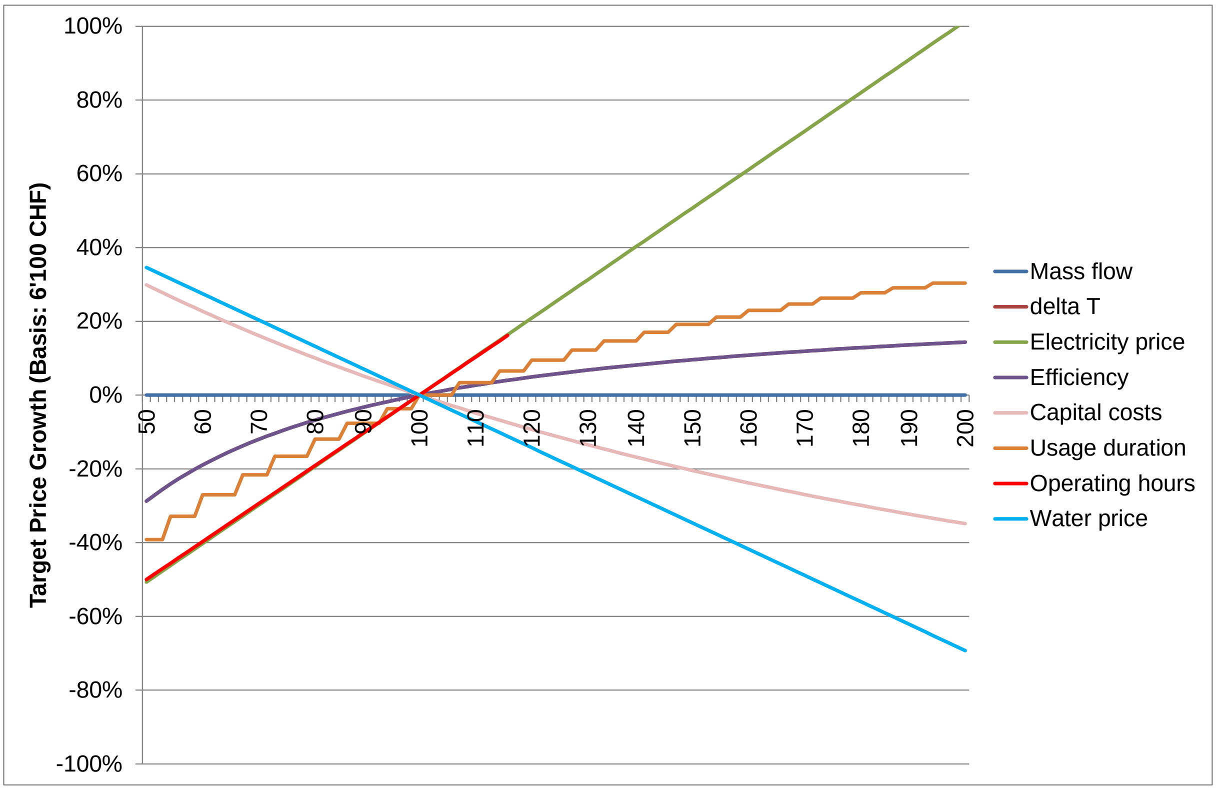
Figure 6 shows the comparison of all input values on the target price per kW installed power. The horizontal axis shows the standardized variation of the input values, the vertical axis shows the growth of the target price. Using the example of the price of electricity, a doubling of the price of electricity (from Index 100 to 200) would cause a doubling of the target price (100% growth). Or a doubling of the thermal efficiency would allow a 15% more expensive machine.

The electricity and water price have the strongest impacts on the profitability. The operating hours would have the same potential as the electricity price if they were not naturally limited. The second most important influence factors are the duration of use and the capital costs, followed by the efficiency, which has identical effects to ΔT. The mass flow has no influence, since the cash flow grows proportionally to the power increase.

Concretely, this means that a doubling of the price of electricity would have a sixfold greater effect on the target price when compared to a doubling of the efficiency. Halving the cost of capital has double the effect of a doubling of ΔT or of the efficiency.

The technical specifications of the machine therefore have a much smaller influence on the profitability than economical values, however they may be directly influenced. The price of electricity and cost of capital are given by the market. The price of water is either provided by the regulator or is defined via the operating costs (e.g. cooling tower). Here, it is important to identify innovative concepts for the integration into processes in order to keep the costs low (e.g. recycling of cooling water). Simultaneously, the available ΔT and the mass flow may be optimized. The efficiency and the operating hours can be increased by technical developments, contrary to the other factors. A small maintenance window and a high reliability increase the operating hours. This argument should not be forgotten when considering figure 6.

Figure 7: Comparison of input values for target price sensitivity analysis (standardized)



Note: Since in the base scenario for case 2, no water costs exist, a proportional modification is not possible. Therefore the selected water price is located in the area between -0.025 and 0.05 CHF. Since in the base scenario we calculate with 85% of the maximum yearly operating hours, a doubling is practically impossible. The maximum increase is of 17% resp. 1.17.

7 Market potential estimation

The largest market potential is assumed to be in the industries identified in section 4.3 and in Kitanovski et al. (2008b). The estimation of the market potential assumes that respectively 50% of the companies have a usable hot and cold water source. Due to the primary energy use of the individual industries, the installation size is approximated. Furthermore, we assume that 80% of the used primary energy is available in the form of waste heat and is produced on average during 7'500 hours per year. The market potential in CHF was calculated with a sales price of 5'000 CHF/kW.

The market potential comprises an estimated 26.5 Mio. CHF in Switzerland and 1.6 Bn. CHF in Germany. Therefore, the market potential is more than sufficiently available in both countries.

7.1 Market potential estimation for Switzerland

Table 4: Estimated market potential for Switzerland. Source: Federal Office for the Environment FOEN, Schober, Wikipedia

Industry	Potential number of machines/type			**Total**
	kW 1-5	kW6-49	kW 50-200	
Pharmaceutical chemistry manufacturers			21	**21**
Smelting works, iron, steel and roller mills			5	**5**
Wood plate manufacturers			2	**2**
Food producers		38		**38**
Paper and cardboard producers		9		**9**
Cement factories			1	**1**
Refineries (all company sizes)			1	**1**
Waste incineration plant (all company sizes)			8	**8**
Total machines Switzerland	**-**	**47**	**38**	**85**
Total power Switzerland (kW)	**-**	**500**	**4'800**	**5'300**
Total market potential Switzerland (Mio. CHF)	**-**	**2.5**	**24.0**	**26.5**

7.2 Market potential estimation for Germany

Table 5: Estimated market potential for Germany. Source: Destatis, Eurostat, Bauen und Umwelt institute (2010), Schober, vdz (2014), Wikipedia.

Industry	**Total number of machines**
Pharmaceutical chemistry manufacturers	**89**
Smelting works, iron, steel and roller mills	**113**
Wood plate manufacturers	**36**
Food producers	**416**
Paper and cardboard producers	**123**
Cement factories	**27**
Refineries	**9**
KVA	**35**
Total machines Germany	**848**
Total power Germany(kW)	**320’000**
Total market potential Germany (Mio. CHF)	**1’600**

8 CO_2 saving potential

The CO_2 saving potential is calculated on the basis of the market potential analysis. The official conversion factor of the Swiss suppliers electricity mix provided by FOEN (2014) of 122 g CO2eq/kWh was used as conversion factor. This factor is of 558 g CO2/kWh (Icha 2014) for Germany.

	Switzerland	Germany
CO2 saving potential	approx. 4'800 t	approx. 1.3 Mio. t
Total emissions 2013	approx. 57 Mio. t	approx. 820 Mio. t

9 Requirements specification

Space requirements
Since the total efficiency is strongly dependent on the required pump energy, the MCM should be placed as close as possible to the water sources. The water plants of the companies are however usually dimensioned pretty tightly, the machine may in some cases have to be set up on stilts or on the roof, which would require additional pump energy.

It is therefore recommended that along with the advantages of a closed system, e.g. in a container, to also consider an "open" integration alternative in order to minimize the space requirements,.

Reliability
Since the MCM is at the end of the production process in (almost) all cases, the reliability does not have a primordial role. The mass flows would be redirected over a bypass and directly mixed in the event of malfunction of the MCM. The thermal power normally retrieved by the machine is negligible, in any case it can lead to slightly higher (environmental) fees. In the case where the machine would be integrated at the start or within the process, a bypass should also be installed, since the complete production process often depends on a functioning cooling water circuit.

Maintenance
Production processes often run 24 hours a day, 365 days a year. Thanks to an over-dimensioned machine park, the maintenance of the production machines can run in parallel with production. As just discussed, the MCM should be secured by a bypass in most cases. The maintenance interval thereby exclusively has a negative effect on the own operating hours. In the sensitivity analysis, we show that the number of operating hours has the largest positive effect on the profitability (as does the price of electricity).

Water separation
The water quality of the cold and hot water is almost never identical in the industry. Mixing of both fluids always has a negative impact on the production process. This is easiest to illustrate in the chemical industry, where the hot water becomes contaminated by chemicals. Mixing the hot with the cold water would declassify the cold water directly into waste water, which needs separate treatment and therefore leads to significant cost increases.

A strict separation of the water flows is imperative in the future, in order to extend the range of applications. Alternately, the problem may also be solved using heat exchangers.

10 Conclusion

10.1 Target price for the profitable operation of MCM

The market pays between 4'500 and 8'100 CHF/kW for an MCM. This price should cover both the production, installation costs and the margin. The price is reached as long as the assumed efficiency of 40% of the Carnot efficiency is reached on the technical side (see preamble).

On the market side, high electricity prices, long operating hours, cheap water and low costs of capital help the profitability of the MCM. A taxation of the waste heat or CO_2would be further positive factors.

10.2 Estimation of MCM success potential

Conditioned by the high involvement for the more optimal use of the waste heat, we estimate the success potential of MCM (as long as the values defined in section 5 are reached) as very high: All contacted companies have a very good consciousness of the issues and actively seek solutions to improve the use of waste heat. As an indicator for high involvements, we not only take the readiness to provide answers in the scope of interviews but that to subsequently provide data.

It should also be noted that almost all contacted companies have a person responsible for the optimized energy usage (Responsible for energy or the environment).

It is not unlikely that the energy price will rise again in the medium term as the market adjusts (subventions for solar and wind energy in Germany). As shown in section 6, the energy price has the strongest positive effect on the profitability of MCM.

Additionally, it should be stated that future regulations may lead to an increase in demand for waste heat usage technologies. Currently the ISO standard 50'001 for energy management in companies might be mentioned. To our best knowledge, there are currently no plans for taxation of waste heat, however this could become a realistic scenario in the future. In this case, by reducing waste heat, the MCM could contribute to lower the tax fee.

From a social perspective, the reduction of CO_2 emissions and the reduced dependence are further positive aspects of the MCM technology. Since the MCM transforms a part of the waste heat into energy and thereby cools down the water in the overall balance, no negative effects on surface or ground water are expected.

10.3 Competitiveness against renewable energy technologies

For the comparison of different energy technologies, the actual costs per kWh are relevant along with the investment costs per kW. The Levelized Cost of Electricity[12](LCOE) compare the accumulated investment and operating costs with the yearly energy production. The LCOE offer a good indicator for the comparison, however they do not represent all aspects of the energy production and the political framework conditions. (Kost et al., 2013)

Figure 7 shows the comparison between the MCM technology and other renewable technologies (blue points). The green rhomboids show the market perspective, i.e. if sales were made at target price. The

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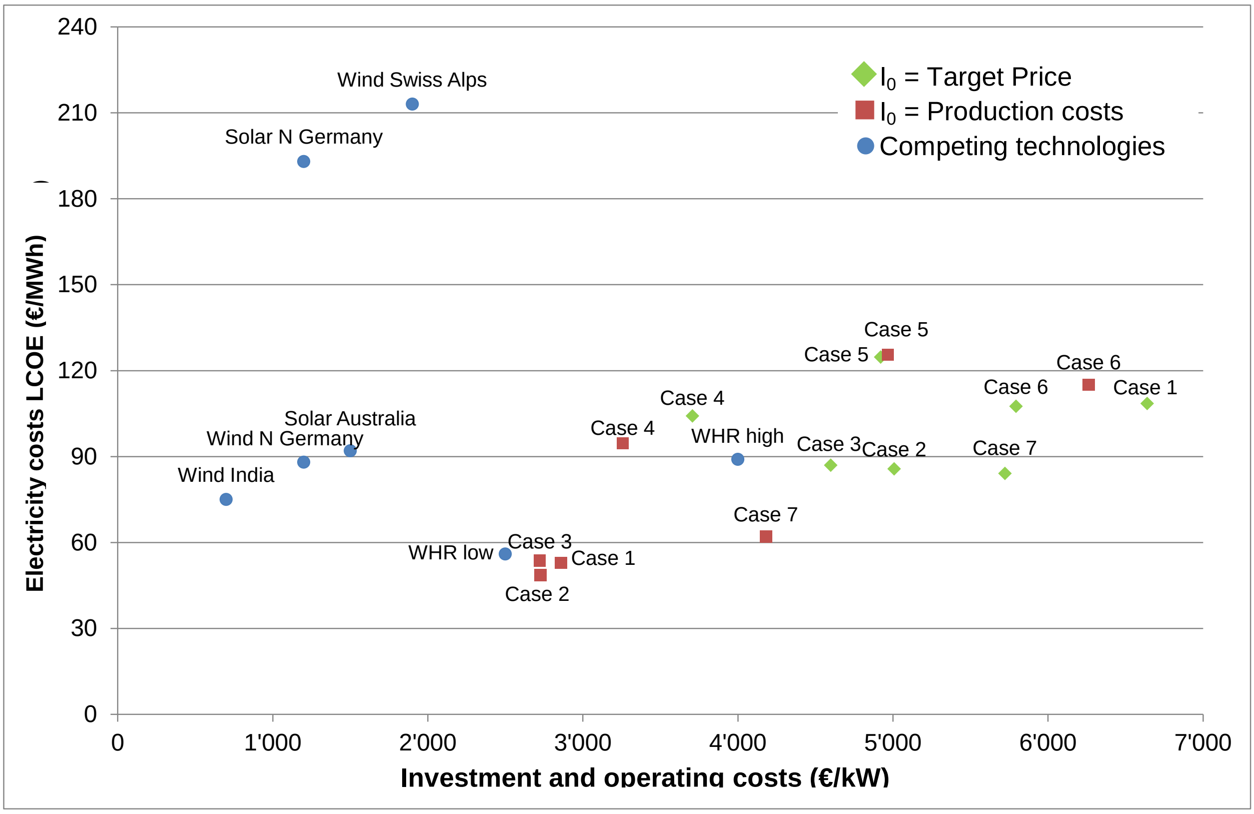
[12] $LCOE = \frac{I_0 + \sum_{t=1}^{T} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{T} \frac{M_{t,el}}{(1+i)^t}}.$

I_0: *Investment costs*, A_t: *Operating costs*, $M_{t,el}$: *produced quantity of electricity in kWh* red squares show the cost perspective, i.e. if the sales price were only to cover the production costs[13]. These are the limit points between which the price and LCOE would move in reality. The real point will therefore lie in this area.

If sales are made at target price, the MCM technology can compete with other technologies in terms of LCOE. The investment and operating costs however are on a very high level. If the effective production costs are however taken into account, the cost per kW sinks to a competitive level for the profitable installations. In particular, the large MCM installations would constitute strong competition to current technologies. It should be noted that the production costs strongly depend on the technological development of the MCM and therefore are currently quite hard to estimate.

Figure 8: Comparison of LCOE and investment costs with renewable energy technologies. Source: Holcim Technology Ltd. Switzerland, own calculation



13 The production costs were estimated by the ITFE based on data from the demonstrator and prototype. The costs are the sum of a fixed part (Generator, housing etc.) and a part depending on the MCM power. The material requirements of these variable costs can easily be divided on a magnet slot, and was also estimated that way. Large installations can better cover the fixed costs (decreasing average costs) and thereby reach lower production costs per kW. A division of the estimated costs can be found in section 12.2.

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Appendix

12 Investment costs calculation

12.1 Net present value method (NPV)

We use the net present value method (NPV) to evaluate the profitability. This method is based on the thought that investment costs are weighed against all future cash flows. The cash flows are thereby discounted at the time of investment. The capital is bound by the investment and should therefore achieve a minimum return, that could for example be achieved by another investment or that reflects the factors such as market opportunities and investment risks. (Thommen, 2012).

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t} + \frac{L_T}{(1+i)^T}$$

$I_0 \ldots Investment\ sum\ at\ time\ 0$
$CF_t \ldots Cash\ flow\ at\ time\ t\ (Revenues - Expenditures)$
$i \ldots capital\ costs$
$L_T \ldots Liquidation\ revenue\ at\ the\ end\ of\ the\ period\ of\ use$
$T \ldots Duration\ of\ use$

If the sum of the discounted cash flows is larger than the investment sum, a positive NPV results. This means that the investment yields a return over the assumed duration of use that is above the required minimum return. (Thommen, 2012)

12.1.1 Target price

An investment should be made as soon as there is a positive NPV. This property is used for the calculation of the target price. If we set the NPV to zero, we can solve according to the investment sum I_0, which corresponds to the target price.

$$Target\ Price = \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t}$$

The target price corresponds to the maximum price achievable on the market. It should cover both the production costs and the margin. The higher the target price, the greater the scope for the production costs, or the greater the margin.

12.1.2 Expenditures and returns - Cash flow

The yearly cash flow results from the sum of the achieved revenues minus the sum of the expenditures. The sum of the revenues and expenditures was elaborated in collaboration with the institute for thermo- and fluid-engineering of the FHNW.

The MCM produces electrical energy that is consumed by the company itself. The energy costs of the company are thereby reduced by the power produced yearly. The price is given by the price paid for electricity by the company (average value including network fees). The revenues are calculated as follows:

$$E_t = Price_{el} * Operating\ hours * P_{el.MCM}$$

The yearly expenditures are the sum of the cost of the mass flows and the electricity costs for pumping.

$$A_t = [Price_H * \mathring{m}_H + Price_C * \mathring{m}_C + Price_{el}(P_{Pump\ \ H} + P_{Pump\ \ C}) + \frac{(\mathring{m}_H + \mathring{m}_C)}{100} * K_{M\&O}] * Operating\ hours$$

H ... hot fluid
C ... cold fluid
P ... power
$\mathring{m}$ ... Mass flow
$Price_{el}$ ... Price of electricity
$K_{M\&O}$ ... Maintenance and operating costs

12.1.3 Considered factors

The investment cost calculation takes the following points into account due to the selected method:

- Capital costs
- Usage duration
- Operating hours
- Pressure losses within the machine
- Pump energy per altitude meter
- Costs for pump energy
- Maintenance and operating costs
- Price of electricity
- Water price

The power of the machine is determined by:

- Efficiency
- ΔT
- Water mass flow

12.2 Investment costs

The costs of an MCM are composed of a fixed component (Generator, drive, water supply, commissioning etc.) and a variable component (magneto-caloric material, magnets, pumps etc.). The cost calculation is performed using the required number of magnet slots. Each magnet slot produces the same electrical power with identical material requirements. The number of magnet slots multiplied by their power gives the total power of the machine.

Positive scale effects occur, which can be explained by declining average costs (lower share of fixed costs on total costs). Besides the fixed costs, which can probably be significantly reduced in the future thanks to cheaper materials and automated production, the number of required magnet slots are the main cost drivers. The costs per magnet slot are mainly dependent on the material and magnet costs. The required number is mainly defined by the available electrical power per magnet slot. The variable investment costs almost decline proportionally to the power per magnet slot. In order to achieve a high profitability, not only the efficiency of the material but also the power per magnet slot need to be increased on the technical side.

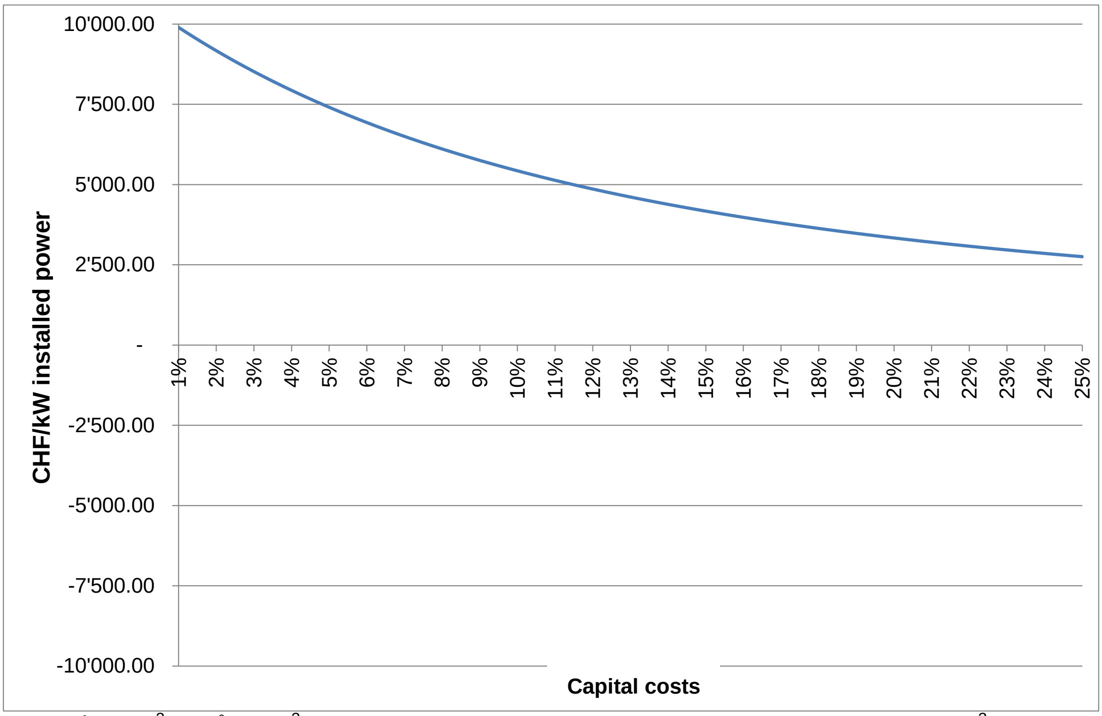
The costs were grossly estimated by ITFE. The estimation is based on the current known values from the construction of the demonstrator and the prototype. The fixed costs were estimated for three installation sizes, the variable costs per magnet slot are identical for all installation sizes (see Table 6).

Table 6: Production cost estimation for three MCM installation sizes.

MCM power	Fixed costs	Variable costs (per magnet slot)
1-5 kW	75’000	5’000
6-50 kW	95’000	5’000
51-200 kW	130’000	5’000

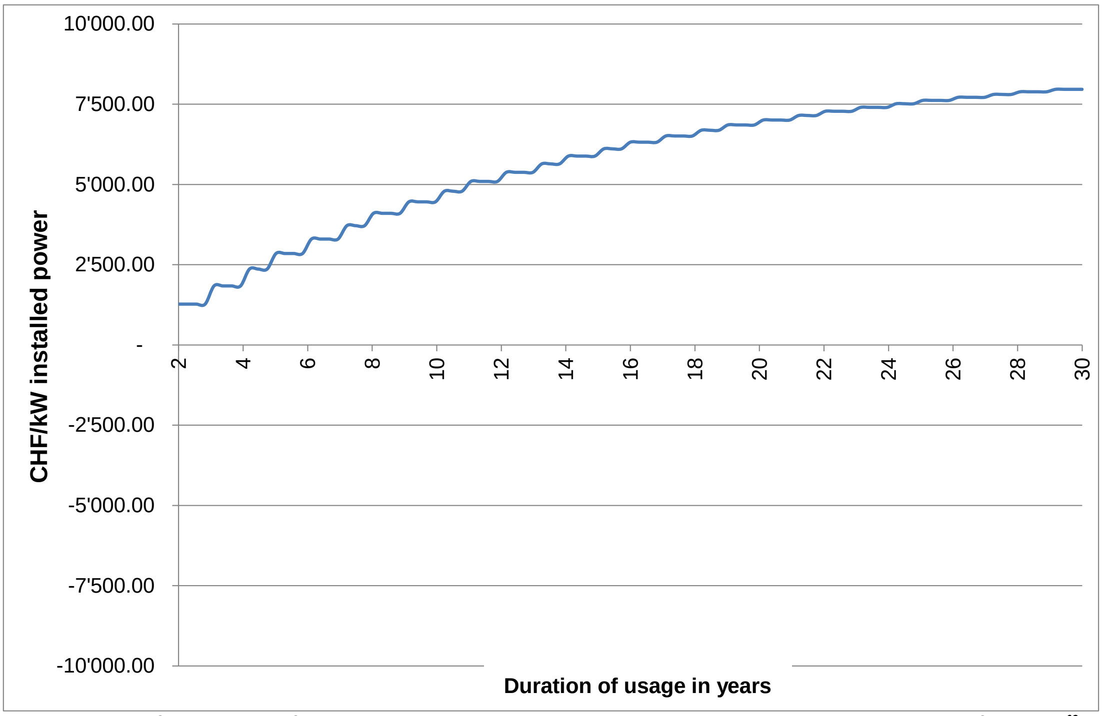
13 Diagrams for sensitivity simulation

Figure 9: Target price depending on capital costs.



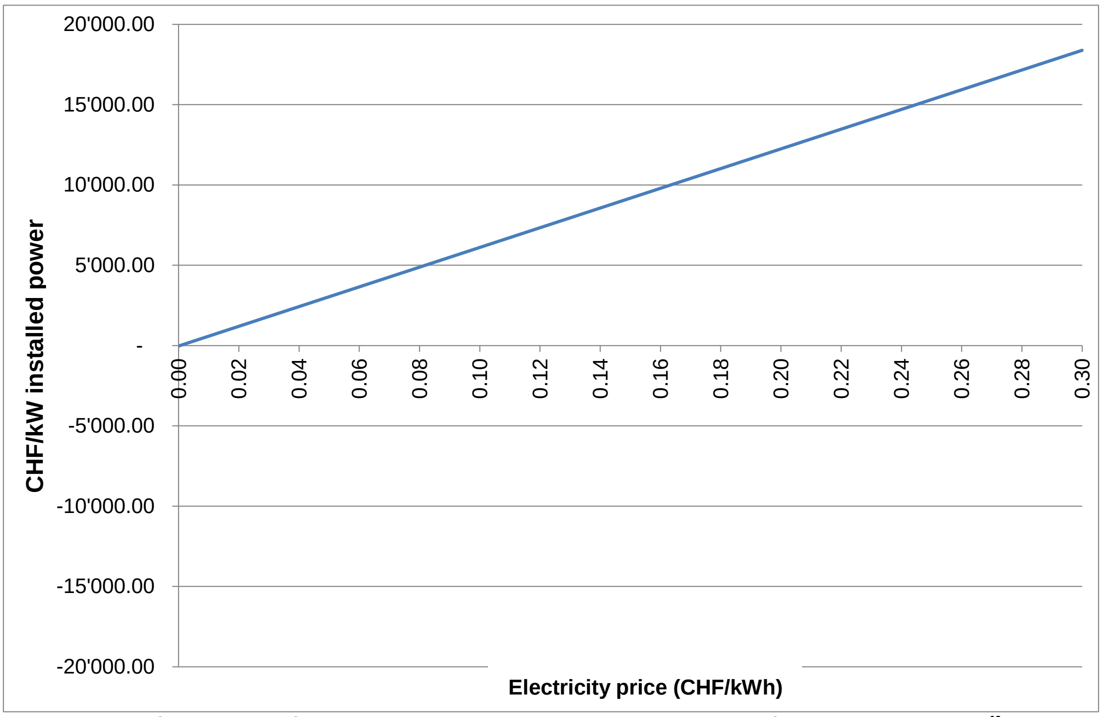
Note: $\mathring{m}_H$=60m^3/h, $\mathring{m}_C$=60m^3/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh, P_{Water}=0.00CHF/m^3, T=15 years, $\eta_{th}/\eta_{carnot} = 40\%,\ Operating\ hours = 7'500h/a.$

Figure 10: Target price depending on duration of usage



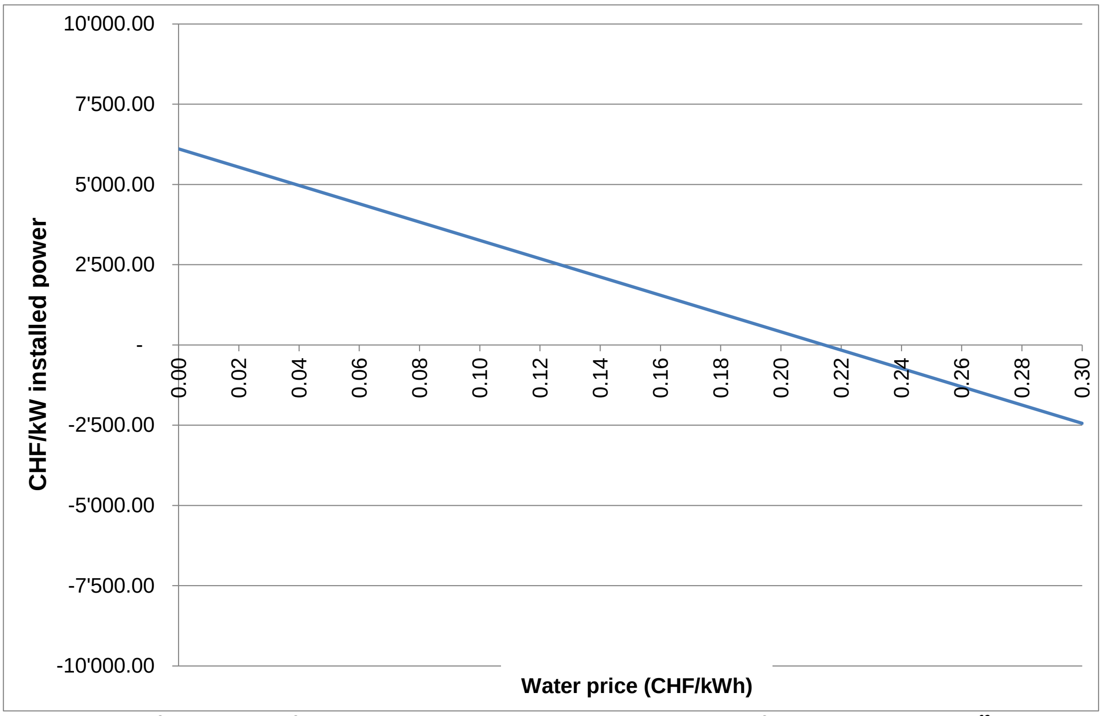
Note: $\mathring{m}_H$=60m^3/h, $\mathring{m}_C$=60m^3/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh, P_{Water}=0.00CHF/m^3, i=8%, ${}^{\eta_{th}}/_{\eta_{carnot}} = 40\%,\ Operating\ hours = 7'500h/a.$

Figure 11: Target price depending on the price of electricity.



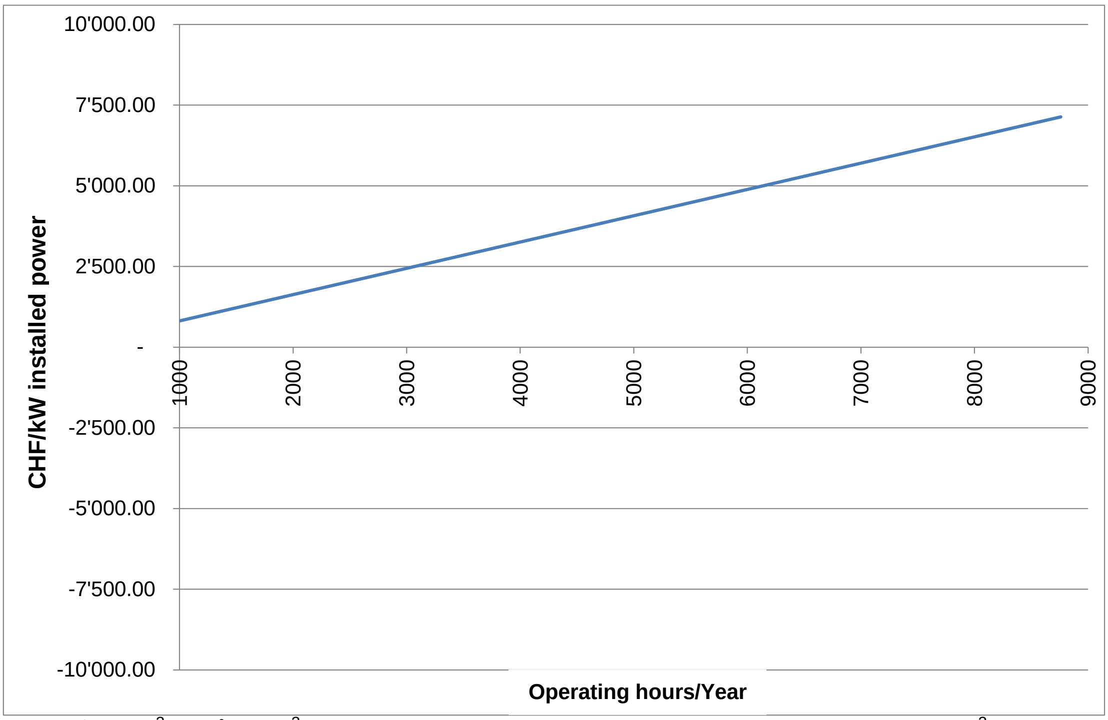
Note: $\mathring{m}_H$=60m^3/h, $\mathring{m}_C$=60m^3/h, $T_H = 57°C, T_C = 17°C, P_{Water}$=0.00CHF/m^3, i=8%, T=15 years, ${}^{\eta_{th}}/_{\eta_{carnot}} = 40\%,$ $Operating\ hours = 7'500h/a.$

Figure 12: Target price depending on the water price.



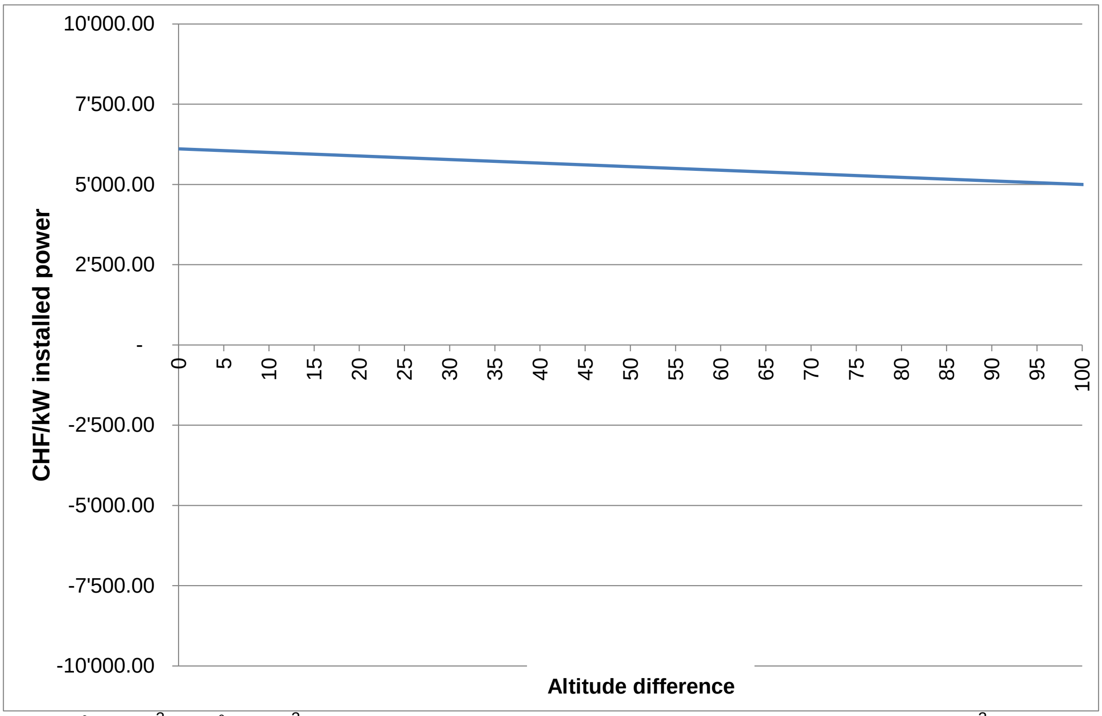
Note: $\mathring{m}_H$=60m³/h, $\mathring{m}_C$=60m³/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh³, i=8%, T=15 years, $\eta_{th}/\eta_{carnot} = 40\%$, $Operating\ hours = 7'500 h/a$.

Figure 13: Target price depending on the operating hours per year.



Note: $\mathring{m}_H$=60m³/h, $\mathring{m}_C$=60m³/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh, P_{Water}=0.00CHF/m³, i=8%, T=15 years, $\eta_{th}/\eta_{carnot} = 40\%$.

Figure 14: Target price depending on the altitude difference to be overcome by the pump energy.



Note: $\mathring{m}_H$=60m³/h, $\mathring{m}_C$=60m³/h, $T_H = 57°C, T_C = 17°C, P_{el}$=0.10CHF/kWh, P_{Water}=0.00CHF/m³, i=8%, T=15 years, $\eta_{th}/\eta_{carnot} = 40\%,\ Operating\ hours = 7'500 h/a.$