Big Solar Feldbach

TRNSYS simulations

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Front page
Arial photo of the 37,500 m^2 solar plant in Dronninglund, DK, as well as the 60,000 m^3 pit heat storage (with the light gray lid in the upper left part of the photo).

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1 Introduction

The district heating production in Feldbach is currently dominated by heat from fossil fuels (natural gas boilers). For various reasons the heat production has to be changed in the coming years, and solar thermal might be a part of the future solution.

As part of a feasibility study of a solar thermal system S.O.L.I.D. has asked PlanEnergi to perform TRNSYS simulations of the energy system.

In this report simulation results are presented.

PlanEnergi

2 Overview of the TRNSYS model

The current version of the TRNSYS model is Feldbach_v17.tpf.

The main parts of the graphical user interface of the model are shown in figure 1.

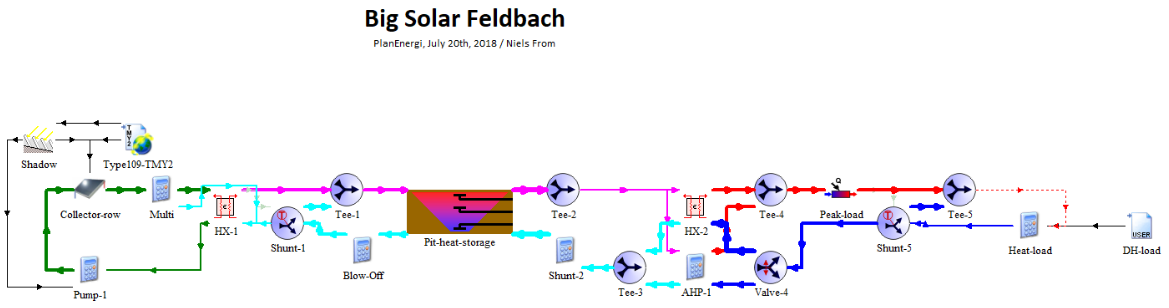

Figure 1: *The graphical user interface of the TRNSYS model. The arrows are transferring data, e.g. temperatures and flows, from one component to another. Some layers are not shown.*

The model consists of 3 circuits separated by the heat exchangers HX-1 and HX-2 and the absorption heat pump AHP-1.

The first circuit is the collector field (with green arrows) in the left-hand side of the model. This circuit contains glycol.

The second circuit contains pit heat storage water (with purple and light blue arrows) in the middle of the model.

The third circuit contains district heating water (with red and dark blue arrows) in the right-hand side of the model.

More details of the TRNSYS model can be found in appendix A.

3 Simulation inputs

The energy system consists of 3 major components:

- A solar plant (collectors and heat exchanger)
- A thermal storage (pit heat storage or steel accumulation tank)
- An absorption heat pump (AHP) (driven by hot water from a natural gas boiler)

The purpose of this work is to find optimal sizes of these components. Optimum is here defined as the system with the lowest (specific investment) = (total investment) divided by the (yearly renewable net production) in [€/MWh/year].

The investments are calculated as shown in appendix C.

The yearly renewable net production is calculated with the TRNSYS model. Details of the TRNSYS model can be found in appendix A. Some of the inputs are:

- DH temperatures and DH load are shown in appendix D
- Ambient temperature and radiation is Meteonorm for Graz
- Collector efficiency parameters are 0.817 – 2.205 – 0.0135 (aperture area)

3 different scenarios have been analyzed:

1. A collector field without area limitations, a steel accumulation tank and an AHP.
2. A collector field and a pit heat storage of up to 25,000 m^2 of land area, and an AHP.
3. A collector field and a pit heat storage without area limitations, and an AHP.

The scenarios have been analyzed with parametric variations as well as numerical optimization.

4 Simulation results

4.1 Scenario # 1: Steel accumulation tank

The table below shows the results of a parametric variation of scenario # 1, where the size of the steel tank is fixed at 5,000 m^3. The collector aperture area is varied between 0 and 20,000 m^2, and the AHP is varied between 0 and 5 MW heat output.

Net production [MWh/y]		0,000 m2	2,000 m2	4,000 m2	6,000 m2	8,000 m2	10,000 m2	12,000 m2	14,000 m2	16,000 m2	18,000 m2	20,000 m2
	0 MW	0	658	1,236	1,787	2,316	2,812	3,257	3,680	4,090	4,488	4,877
	1 MW	3	1,365	2,165	2,666	3,146	3,600	4,017	4,403	4,741	5,085	5,434
	2 MW	5	1,411	2,306	3,077	3,790	4,363	4,786	5,232	5,658	6,039	6,406
	3 MW	6	1,440	2,344	3,140	3,901	4,640	5,214	5,672	6,105	6,550	6,992
	4 MW	6	1,459	2,364	3,166	3,935	4,696	5,352	5,851	6,301	6,745	7,201
	5 MW	6	1,472	2,377	3,179	3,951	4,715	5,389	5,917	6,390	6,823	7,278

Specific production [kWh/m2/y]		0,000 m2	2,000 m2	4,000 m2	6,000 m2	8,000 m2	10,000 m2	12,000 m2	14,000 m2	16,000 m2	18,000 m2	20,000 m2
	0 MW		329	309	298	289	281	271	263	256	249	244
	1 MW		683	541	444	393	360	335	315	296	282	272
	2 MW		706	576	513	474	436	399	374	354	335	320
	3 MW		720	586	523	488	464	434	405	382	364	350
	4 MW		730	591	528	492	470	446	418	394	375	360
	5 MW		736	594	530	494	472	449	423	399	379	364

Solar fraction 32,000	MWh/y	0,000 m2	2,000 m2	4,000 m2	6,000 m2	8,000 m2	10,000 m2	12,000 m2	14,000 m2	16,000 m2	18,000 m2	20,000 m2
	0 MW	0%	2%	4%	6%	7%	9%	10%	12%	13%	14%	15%
	1 MW	0%	4%	7%	8%	10%	11%	13%	14%	15%	16%	17%
	2 MW	0%	4%	7%	10%	12%	14%	15%	16%	18%	19%	20%
	3 MW	0%	5%	7%	10%	12%	14%	16%	18%	19%	20%	22%
	4 MW	0%	5%	7%	10%	12%	15%	17%	18%	20%	21%	23%
	5 MW	0%	5%	7%	10%	12%	15%	17%	18%	20%	21%	23%

Investment [M€]		0,000 m2	2,000 m2	4,000 m2	6,000 m2	8,000 m2	10,000 m2	12,000 m2	14,000 m2	16,000 m2	18,000 m2	20,000 m2
	0 MW	1.05	1.41	1.77	2.13	2.49	2.85	3.21	3.57	3.93	4.29	4.65
	1 MW	1.35	1.71	2.07	2.43	2.79	3.15	3.51	3.87	4.23	4.59	4.95
	2 MW	1.47	1.83	2.19	2.55	2.91	3.27	3.63	3.99	4.35	4.71	5.07
	3 MW	1.57	1.93	2.29	2.65	3.01	3.37	3.73	4.09	4.45	4.81	5.17
	4 MW	1.65	2.01	2.37	2.73	3.09	3.45	3.81	4.17	4.53	4.89	5.25
	5 MW	1.72	2.08	2.44	2.80	3.16	3.52	3.88	4.24	4.60	4.96	5.32

Specific investment [€/MWh/y]		0,000 m2	2,000 m2	4,000 m2	6,000 m2	8,000 m2	10,000 m2	12,000 m2	14,000 m2	16,000 m2	18,000 m2	20,000 m2
	0 MW			1,433	1,192	1,075	1,013	985	970	961	956	953
	1 MW		1,252	956	911	887	875	874	879	892	903	911
	2 MW		1,300	952	830	769	750	759	763	770	781	792
	3 MW		1,340	977	844	771	726	715	721	729	734	739
	4 MW		1,378	1,003	862	785	735	712	713	719	725	729
	5 MW		1,414	1,027	881	800	747	720	717	720	727	731

In the top of the table the net production is shown. As expected the production increases when the collector area and/or the size of the AHP are increased.

The specific production is defined as the net production divided by the collector area.

The solar fraction is defined as the net production divided by the yearly heat demand (32,000 MWh/y). The max. solar fraction is 23% (with 20,000 m^2 collectors and min. 4 MW AHP).

The investment is between 1.1 and 5.3 mio. €. As expected the investment increases when the collector area and/or the size of the AHP are increased.

In the bottom of the table the specific investment is shown. The lowest value is 712 €/MWh/y (with 12,000 m^2 collectors and an AHP of 4 MW).

4.1.1 Numerical optimization

A numerical optimization has been performed where all 3 parameters has been varied. The optimum parameters are found to be:

- Collector aperture area = 12,750 m^2
- Steel tank volume = 2,000 m^3 (minimum constraint)
- AHP heat output capacity = 3.1875 MW

These parameters give the following values:

- Net production = 5,308 MWh/y
- Specific production = 416 kWh/m^2/y
- Solar fraction = 17%
- Investment = 3.58 mio. €
- Specific investment = 675 €/MWh/y

4.2 Scenario # 2: Pit heat storage + collectors = 25,000 m² land area

The table below shows the results of a parametric variation of scenario # 2, where the footprint of the pit heat storage is 25,000 m² minus 2.0 times the collector aperture area. The footprint of the pit heat storage is varied between 10,000 and 25,000 m² (and the corresponding collector aperture area is between 7,500 and 0 m². The AHP is varied between 0 and 5 MW heat output.

PTES	m2	10000	11000	12000	13000	14000	15000	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000
25000	Coll.	15000	14000	13000	12000	11000	10000	9000	8000	7000	6000	5000	4000	3000	2000	1000	0
		7.5	7	6.5	6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1	0.5	0
Net production																	
[MWh/y]		7.500 m2	7,000 m2	6.500 m2	6,000 m2	5.500 m2	5,000 m2	4.500 m2	4,000 m2	3.500 m2	3,000 m2	2.500 m2	2,000 m2	1.500 m2	1,000 m2	0.500 m2	0,000 m2
	0 MW	2,047	1,884	1,662	1,355	798	118	0	0	0	0	0	0	0	0	0	0
	1 MW	3,487	3,335	2,945	2,870	2,870	2,870	2,780	2,568	2,279	1,945	1,585	1,230	872	506	171	3
	2 MW	4,568	4,381	4,233	4,033	3,775	3,478	3,154	2,807	2,444	2,076	1,704	1,321	932	553	199	6
	3 MW	4,709	4,556	4,376	4,138	3,859	3,550	3,216	2,864	2,499	2,126	1,746	1,357	967	581	213	7
	4 MW	4,761	4,609	4,423	4,180	3,896	3,584	3,249	2,895	2,526	2,151	1,769	1,381	988	598	222	7
	5 MW	4,789	4,637	4,448	4,202	3,918	3,600	3,265	2,910	2,541	2,167	1,782	1,394	1,000	607	226	7
Specific production																	
[kWh/m2/y]		7.500 m2	7,000 m2	6.500 m2	6,000 m2	5.500 m2	5,000 m2	4.500 m2	4,000 m2	3.500 m2	3,000 m2	2.500 m2	2,000 m2	1.500 m2	1,000 m2	0.500 m2	0,000 m2
	0 MW	273	269	256													
	1 MW	465	476	453	478	522	574	618	642	651	648	634	615	581	506	341	
	2 MW	609	626	651	672	686	696	701	702	698	692	682	661	621	553	397	
	3 MW	628	651	673	690	702	710	715	716	714	709	698	679	645	581	427	
	4 MW	635	658	680	697	708	717	722	724	722	717	707	690	659	598	444	
	5 MW	638	662	684	700	712	720	726	727	726	722	713	697	667	607	453	
Solar fraction																	
32000		7.500 m2	7,000 m2	6.500 m2	6,000 m2	5.500 m2	5,000 m2	4.500 m2	4,000 m2	3.500 m2	3,000 m2	2.500 m2	2,000 m2	1.500 m2	1,000 m2	0.500 m2	0,000 m2
	0 MW	6%	6%	5%	4%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1 MW	11%	10%	9%	9%	9%	9%	9%	8%	7%	6%	5%	4%	3%	2%	1%	0%
	2 MW	14%	14%	13%	13%	12%	11%	10%	9%	8%	6%	5%	4%	3%	2%	1%	0%
	3 MW	15%	14%	14%	13%	12%	11%	10%	9%	8%	7%	5%	4%	3%	2%	1%	0%
	4 MW	15%	14%	14%	13%	12%	11%	10%	9%	8%	7%	6%	4%	3%	2%	1%	0%
	5 MW	15%	14%	14%	13%	12%	11%	10%	9%	8%	7%	6%	4%	3%	2%	1%	0%
PTES	m3	23,000	29,060	35,120	41,180	47,240	53,300	59,360	65,420	71,480	77,540	83,600	89,660	95,720	101,780	107,840	113,900
Investment																	
[M€]		7.500 m2	7,000 m2	6.500 m2	6,000 m2	5.500 m2	5,000 m2	4.500 m2	4,000 m2	3.500 m2	3,000 m2	2.500 m2	2,000 m2	1.500 m2	1,000 m2	0.500 m2	0,000 m2
	0 MW	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.71	3.71	3.71	3.71
	1 MW	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.01	4.01	4.01	4.01
	2 MW	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
	3 MW	4.21	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.23	4.23	4.23	4.23
	4 MW	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.31	4.31	4.31	4.31
	5 MW	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.38	4.38	4.38	4.38	4.38
Specific investment																	
[€/MWh/y]		7.500 m2	7,000 m2	6.500 m2	6,000 m2	5.500 m2	5,000 m2	4.500 m2	4,000 m2	3.500 m2	3,000 m2	2.500 m2	2,000 m2	1.500 m2	1,000 m2	0.500 m2	0,000 m2
	0 MW																
	1 MW	1,146	1,198	1,357	1,393	1,393	1,393	1,439	1,558								
	2 MW	902	941	973	1,022	1,092	1,186	1,308	1,470								
	3 MW	895	925	963	1,019	1,093	1,189	1,312	1,474								
	4 MW	902	932	972	1,028	1,103	1,200	1,324	1,486								
	5 MW	912	942	982	1,040	1,115	1,214	1,339	1,503								

In the top of the table the net production is shown. As expected the production increases when the collector area and/or the size of the AHP are increased.

The max. specific production is 727 kWh/m²/y (with min. 4,000 m² collectors and 5 MW AHP).

The max. solar fraction is 15% (with min. 7,500 m² collectors and min. 3 MW AHP).

The investment is between 3.7 and 4.4 mio. €. The price for the pit heat storage is almost equal to the price of the solar collectors for the same footprint.

In the bottom of the table the specific investment is shown. The lowest value is 895 €/MWh/y (with 23,000 m^3 pit heat storage, 7,500 m^2 collectors and an AHP of 3 MW). This value is 33% higher than the optimum 675 €/MWh/y is scenario # 1, so scenario # 2 is not competitive.

4.2.1 Numerical optimization

As scenario # 2 is found to be not competitive, a numerical optimization has not been performed for this scenario.

4.3 Scenario # 3: No land area limitations

The table below shows the results of a parametric variation of scenario # 2, where the footprint of the pit heat storage is fixed at 25,000 m^2 (i.e. 116,000 m^3). The collector aperture area is varied between 0 and 50,000 m^2, and the AHP is varied between 0 and 20 MW heat output.

Net production [MWh/y]	0,000 m2	2.500 m2	5,000 m2	7.500 m2	10,000 m2	12.500 m2	15,000 m2	17.500 m2	20,000 m2	22.500 m2	25,000 m2	27.500 m2	30,000 m2	32.500 m2	35,000 m2	37.500 m2	40,000 m2	42.500 m2	45,000 m2	47.500 m2	50,000 m2
0 MW	0	0	0	0	301	2,232	3,994	5,310	6,145	6,716	7,187	7,619	8,053	8,489	8,905	9,301	9,685	10,057	10,419	10,769	11,100
2.5 MW	7	1,645	3,442	5,064	6,383	6,457	6,457	7,036	8,185	9,034	9,632	10,029	10,252	10,501	10,796	11,089	11,384	11,668	11,930	12,175	12,419
5 MW	7	1,707	3,551	5,317	6,937	8,326	9,582	10,453	10,604	11,448	12,154	12,722	13,193	13,422	13,590	13,741	13,860	14,000	14,166	14,342	14,557
7.5 MW	7	1,720	3,570	5,345	6,994	8,489	9,699	10,884	11,912	12,930	13,721	14,369	14,921	15,352	15,524	15,648	15,786	15,921	16,023	16,134	16,271
10 MW	7	1,721	3,573	5,349	7,005	8,515	9,713	10,908	11,949	13,066	14,107	14,906	15,545	16,037	16,287	16,396	16,519	16,656	16,778	16,871	16,981
12.5 MW	7	1,721	3,573	5,349	7,005	8,516	9,715	10,911	11,952	13,070	14,117	14,939	15,606	16,111	16,371	16,480	16,601	16,737	16,861	16,955	17,061
15 MW	7	1,721	3,573	5,349	7,005	8,516	9,715	10,911	11,952	13,070	14,117	14,939	15,606	16,111	16,371	16,480	16,601	16,737	16,861	16,955	17,061
17.5 MW	7	1,721	3,573	5,349	7,005	8,516	9,715	10,911	11,952	13,070	14,117	14,939	15,606	16,111	16,371	16,480	16,601	16,737	16,861	16,955	17,061
20 MW	7	1,721	3,573	5,349	7,005	8,516	9,715	10,911	11,952	13,070	14,117	14,939	15,606	16,111	16,371	16,480	16,601	16,737	16,861	16,955	17,061

Specific production [kWh/m2/y]	0,000 m2	2.500 m2	5,000 m2	7.500 m2	10,000 m2	12.500 m2	15,000 m2	17.500 m2	20,000 m2	22.500 m2	25,000 m2	27.500 m2	30,000 m2	32.500 m2	35,000 m2	37.500 m2	40,000 m2	42.500 m2	45,000 m2	47.500 m2	50,000 m2
0 MW						179	266	303	307	298	287	277	268	261	254	248	242	237	232	227	222
2.5 MW		658	688	675	638	517	430	402	409	402	385	365	342	323	308	296	285	275	265	256	248
5 MW		683	710	709	694	666	639	597	530	509	486	463	440	413	388	366	347	329	315	302	291
7.5 MW		688	714	713	699	679	647	622	596	575	549	523	497	472	444	417	395	375	356	340	325
10 MW		688	715	713	700	681	648	623	597	581	564	542	518	493	465	437	413	392	373	355	340
12.5 MW		688	715	713	701	681	648	623	598	581	565	543	520	496	468	439	415	394	375	357	341
15 MW		688	715	713	701	681	648	623	598	581	565	543	520	496	468	439	415	394	375	357	341
17.5 MW		688	715	713	701	681	648	623	598	581	565	543	520	496	468	439	415	394	375	357	341
20 MW		688	715	713	701	681	648	623	598	581	565	543	520	496	468	439	415	394	375	357	341

Solar fraction 32000	0,000 m2	2.500 m2	5,000 m2	7.500 m2	10,000 m2	12.500 m2	15,000 m2	17.500 m2	20,000 m2	22.500 m2	25,000 m2	27.500 m2	30,000 m2	32.500 m2	35,000 m2	37.500 m2	40,000 m2	42.500 m2	45,000 m2	47.500 m2	50,000 m2
0 MW	0%	0%	0%	0%	1%	7%	12%	17%	19%	21%	22%	24%	25%	27%	28%	29%	30%	31%	33%	34%	35%
2.5 MW	0%	5%	11%	16%	20%	20%	20%	22%	26%	28%	30%	31%	32%	33%	34%	35%	36%	36%	37%	38%	39%
5 MW	0%	5%	11%	17%	22%	26%	30%	33%	33%	36%	38%	40%	41%	42%	42%	43%	43%	44%	44%	45%	45%
7.5 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	40%	43%	45%	47%	48%	49%	49%	49%	50%	50%	50%	51%
10 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	41%	44%	47%	49%	50%	51%	51%	52%	52%	52%	53%	53%
12.5 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	41%	44%	47%	49%	50%	51%	51%	52%	52%	53%	53%	53%
15 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	41%	44%	47%	49%	50%	51%	51%	52%	52%	53%	53%	53%
17.5 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	41%	44%	47%	49%	50%	51%	51%	52%	52%	53%	53%	53%
20 MW	0%	5%	11%	17%	22%	27%	30%	34%	37%	41%	44%	47%	49%	50%	51%	51%	52%	52%	53%	53%	53%

Investment [M€]	0,000 m2	2.500 m2	5,000 m2	7.500 m2	10,000 m2	12.500 m2	15,000 m2	17.500 m2	20,000 m2	22.500 m2	25,000 m2	27.500 m2	30,000 m2	32.500 m2	35,000 m2	37.500 m2	40,000 m2	42.500 m2	45,000 m2	47.500 m2	50,000 m2
0 MW	3.74	4.19	4.64	5.09	5.54	5.99	6.44	6.89	7.34	7.79	8.24	8.69	9.14	9.59	10.04	10.49	10.94	11.39	11.84	12.29	12.74
2.5 MW	4.21	4.66	5.11	5.56	6.01	6.46	6.91	7.36	7.81	8.26	8.71	9.16	9.61	10.06	10.51	10.96	11.41	11.86	12.31	12.76	13.21
5 MW	4.41	4.86	5.31	5.76	6.21	6.66	7.11	7.56	8.01	8.46	8.91	9.36	9.81	10.26	10.71	11.16	11.61	12.06	12.51	12.96	13.41
7.5 MW	4.56	5.01	5.46	5.91	6.36	6.81	7.26	7.71	8.16	8.61	9.06	9.51	9.96	10.41	10.86	11.31	11.76	12.21	12.66	13.11	13.56
10 MW	4.69	5.14	5.59	6.04	6.49	6.94	7.39	7.84	8.29	8.74	9.19	9.64	10.09	10.54	10.99	11.44	11.89	12.34	12.79	13.24	13.69
12.5 MW	4.80	5.25	5.70	6.15	6.60	7.05	7.50	7.95	8.40	8.85	9.30	9.75	10.20	10.65	11.10	11.55	12.00	12.45	12.90	13.35	13.80
15 MW	4.90	5.35	5.80	6.25	6.70	7.15	7.60	8.05	8.50	8.95	9.40	9.85	10.30	10.75	11.20	11.65	12.10	12.55	13.00	13.45	13.90
17.5 MW	4.99	5.44	5.89	6.34	6.79	7.24	7.69	8.14	8.59	9.04	9.49	9.94	10.39	10.84	11.29	11.74	12.19	12.64	13.09	13.54	13.99
20 MW	5.08	5.53	5.98	6.43	6.88	7.33	7.78	8.23	8.68	9.13	9.58	10.03	10.48	10.93	11.38	11.83	12.28	12.73	13.18	13.63	14.08

Specific investment [€/MWh/y]	0,000 m2	2.500 m2	5,000 m2	7.500 m2	10,000 m2	12.500 m2	15,000 m2	17.500 m2	20,000 m2	22.500 m2	25,000 m2	27.500 m2	30,000 m2	32.500 m2	35,000 m2	37.500 m2	40,000 m2	42.500 m2	45,000 m2	47.500 m2	50,000 m2
0 MW								1,298	1,195	1,160	1,147	1,141	1,135	1,130	1,127	1,128	1,130	1,132	1,136	1,141	1,148
2.5 MW				1,099	942	1,001	1,071	1,047	955	915	905	914	938	958	974	989	1,003	1,017	1,032	1,048	1,064
5 MW				1,083	895	800	742	723	755	739	733	736	744	764	788	812	838	861	883	904	921
7.5 MW				1,106	910	802	749	709	685	666	660	662	668	678	700	723	745	767	790	813	833
10 MW				1,129	926	815	761	719	694	669	651	647	649	657	675	698	720	741	762	785	806
12.5 MW				1,150	942	828	772	729	703	677	659	653	654	661	678	701	723	744	765	787	809
15 MW				1,169	957	840	783	738	711	685	666	659	660	667	684	707	729	750	771	793	815
17.5 MW				1,186	970	851	792	747	719	692	673	666	666	673	690	713	735	755	777	799	820
20 MW				1,202	982	861	801	754	726	699	679	671	672	679	695	718	740	761	782	804	825

In the top of the table the net production is shown. As expected the production increases when the collector area and/or the size of the AHP are increased.

The max. specific production is approx. 715 kWh/m^2/y.

The max. solar fraction is 53% (with min. 45,000 m^2 collectors and min. 12.5 MW AHP).

The investment is between 3.7 and 14.1 mio. €. As expected the investment increases when the collector area and/or the size of the AHP are increased.

In the bottom of the table the specific investment is shown. The lowest value is 647 €/MWh/y (with 27,500 m^2 collectors and an AHP of 10 MW).

4.3.1 Numerical optimization

A numerical optimization has been performed where all 3 parameters has been varied. The optimum parameters are found to be:

- Collector aperture area = 28,437.5 m^2
- Pit heat storage volume = 99,000 m^3
- AHP heat output capacity = 7.9375 MW

These parameters give the following values:

- Net production = 14,826 MWh/y
- Specific production = 521 kWh/m^2/y
- Solar fraction = 46%
- Investment = 9.4 mio. €
- Specific investment = 637 €/MWh/y

4.3.2 Row distance and collector slope

In this section the following parameters are fixed:

- Collector aperture area = 30,000 m^2
- Pit heat storage volume = 100,000 m^3
- AHP heat output capacity = 8.0 MW

With these parameters the collector row distance (from the front of one row to the front of the next row) and the collector slope are varied.

It is assumed that varying the collector slope has no impact on the investment.

It is also assumed that varying the row distance has no impact on the investment, and no impact on the heat losses. It is noted that this assumption is not fully realistic as an increased row distance will require more land area and more piping in the ground.

The table below shows the results of the variation.

As expected the net production increases when the row distance is increased.

It can be seen that the optimum slope depends on the row distance, e.g. approx. 15° at 3.0 m, approx. 25° at 4.0 m and approx. 30° at 5.0 m and 6.0 m.

Net production [MWh/y]		3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
	10°	14,032	14,154	14,172	14,180	14,185	14,189	14,192
	15°	14,176	14,480	14,594	14,620	14,631	14,638	14,643
	20°	14,149	14,581	14,816	14,919	14,952	14,967	14,976
	25°	14,006	14,542	14,866	15,061	15,143	15,172	15,187
	30°	13,774	14,387	14,785	15,048	15,173	15,227	15,252
	35°	13,472	14,135	14,593	14,908	15,081	15,164	15,202
	40°	13,122	13,808	14,307	14,662	14,884	14,995	15,051
	45°	12,741	13,430	13,957	14,340	14,604	14,742	14,813
	50°	12,347	13,028	13,551	13,957	14,251	14,415	14,503
	55°	11,847	12,568	13,120	13,531	13,828	14,004	14,101
	60°	11,251	11,956	12,521	12,950	13,273	13,472	13,583

Specific production [kWh/m2/y]		3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
	10°	468	472	472	473	473	473	473
	15°	473	483	486	487	488	488	488
	20°	472	486	494	497	498	499	499
	25°	467	485	496	502	505	506	506
	30°	459	480	493	502	506	508	508
	35°	449	471	486	497	503	505	507
	40°	437	460	477	489	496	500	502
	45°	425	448	465	478	487	491	494
	50°	412	434	452	465	475	481	483
	55°	395	419	437	451	461	467	470
	60°	375	399	417	432	442	449	453

Solar fraction 32000		3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
	10°	44%	44%	44%	44%	44%	44%	44%
	15°	44%	45%	46%	46%	46%	46%	46%
	20°	44%	46%	46%	47%	47%	47%	47%
	25°	44%	45%	46%	47%	47%	47%	47%
	30°	43%	45%	46%	47%	47%	48%	48%
	35°	42%	44%	46%	47%	47%	47%	48%
	40°	41%	43%	45%	46%	47%	47%	47%
	45°	40%	42%	44%	45%	46%	46%	46%
	50°	39%	41%	42%	44%	45%	45%	45%
	55°	37%	39%	41%	42%	43%	44%	44%
	60°	35%	37%	39%	40%	41%	42%	42%

Investment [M€]		3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
	10°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	15°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	20°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	25°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	30°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	35°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	40°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	45°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	50°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	55°	9.75	9.75	9.75	9.75	9.75	9.75	9.75
	60°	9.75	9.75	9.75	9.75	9.75	9.75	9.75

Specific investment [€/MWh/y]		3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
	10°	695	689	688	687	687	687	687
	15°	688	673	668	667	666	666	666
	20°	689	669	658	653	652	651	651
	25°	696	670	656	647	644	643	642
	30°	708	678	659	648	642	640	639
	35°	724	690	668	654	646	643	641
	40°	743	706	681	665	655	650	648
	45°	765	726	698	680	668	661	658
	50°	790	748	719	698	684	676	672
	55°	823	776	743	720	705	696	691
	60°	866	815	779	753	734	724	718

4.3.3 *Energy balances and temperature development*

In this section the following parameters are used:

- Collector aperture area = 30,000 m^2
- Pit heat storage volume = 100,000 m^3
- AHP heat output capacity = 8.0 MW
- Row distance = 4.5 m
- Collector slope = 30°

Key figures and energy balance for year 2			
AHP1_Q_out_max_MW		8	MW
Pit_volume		100,000	m3
Collector_area (aperture)		30,000	m2
Collector height		2.270	m
Row distance		4.500	m
Row distance	1:	1.982	m/m
Storage heat losses		1,754	MWh
Q_heat_load		31,498	MWh
Q_HX1		16,873	MWh
Q_HX2		4,380	MWh
Q_peakload		2,414	MWh
Q_blowoff		3	MWh
Q_ahp_evap		10,668	MWh
Q_ahp_gen		14,036	MWh
Renewable_energy		15,048	MWh
Specific yield		502	kWh/m2/y
Total investment		9,748,528	€
Cost_function		648	€/MWh/y

Figure 2: *Red line = ambient temperature [°C], blue line = DH forward temperature [°C], pink line = DH return temperature [°C] and beige line = max. DH feed in capacity [MW].*

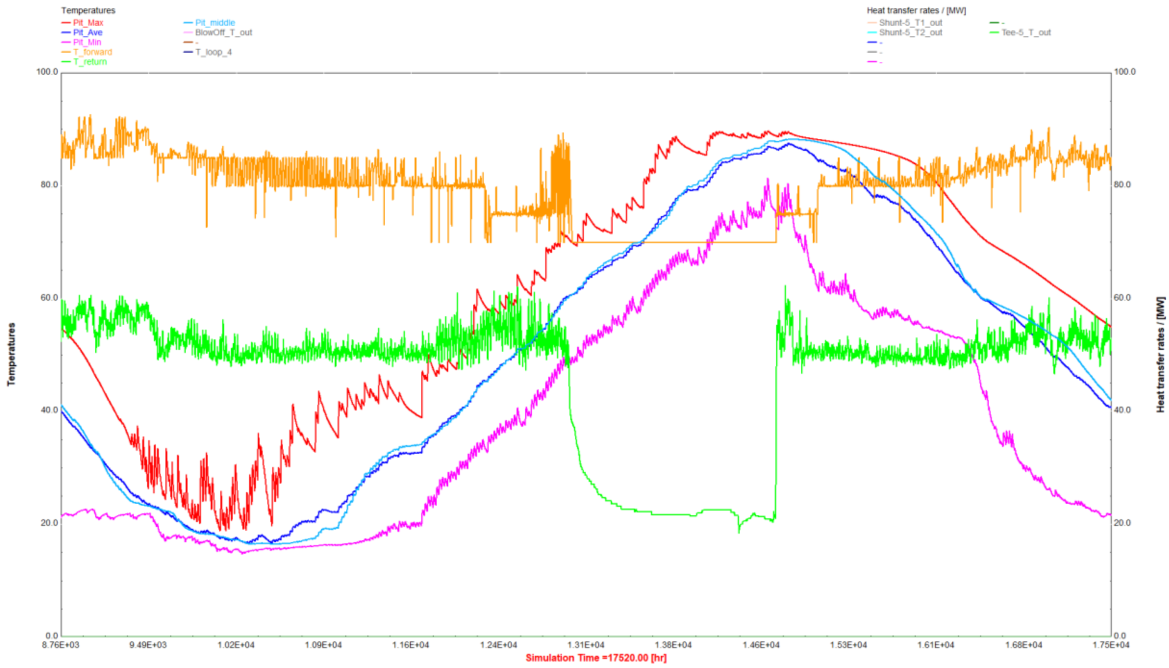

Figure 3: *Yellow and green lines = DH temperatures [°C], red, light blue and pink lines = pit heat storage temperatures [°C] in top, middle and bottom, and dark blue line = average storage temperature [°C]. It is noted that heat above 80°C in the bottom of the storage is wasted during charging.*

Appendix A – Detailed model description

In this appendix the most important details from the TRNSYS model are presented. The details consist of values and equations with comments.

4.4 Graphical user interface

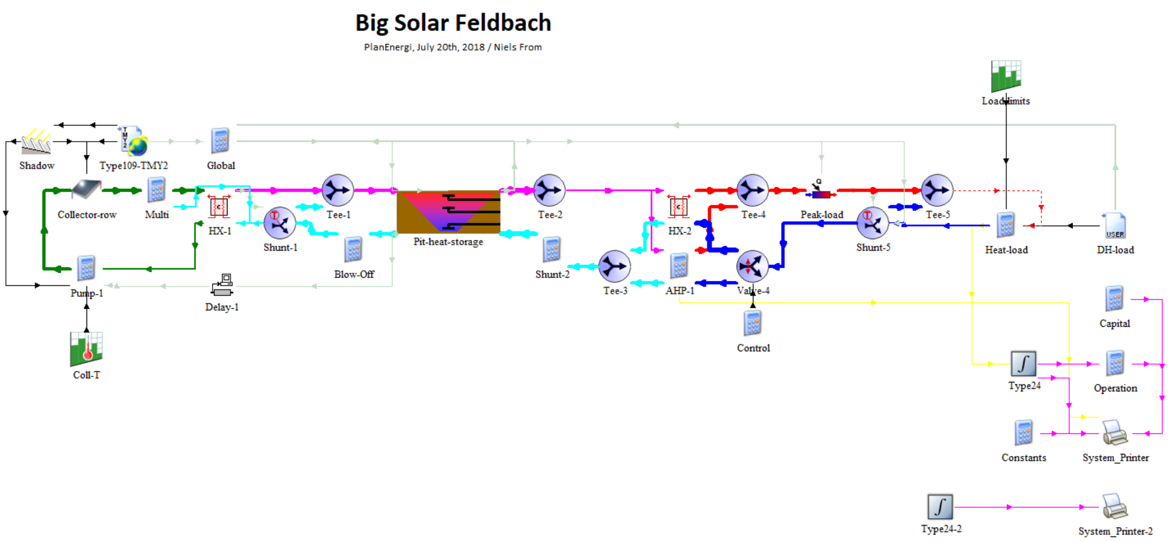

Figure A.1: *The graphical user interface of the TRNSYS model. The arrows are transferring data from one component to another. The model layer "Outputs" is not shown.*

4.5 Simulation details

4.5.1 Control Cards

- Simulation start time = 0 hr
- Simulation stop time = 17,520 hr[1]
- Simulation time step = 1 hr[2]

4.5.2 Simulation cards

- Area_one_string = 200 [m^2][3]
- Collector_area_1000 = 30 [m^2][4]
- Collector_area = Collector_area_1000 * 1,000 [m^2]
- eta_0 = 0.817
- a_1 = 2.205 * 3.6 [kJ/hr.m^2.K]
- a_2 = 0.0135 * 3.6 [kJ/hr.m^2.K^2]
- row_distance = 4.5 [m]
- collector_slope = 30 [°]
- store_volume_1000 = 100 [m^3]
- store_volume = store_volume_1000 * 1,000 [m^3]
- store_lid_area = 0.097 * store_volume + 2355 [m^2]
- store_height = store_volume / store_lid_area [m][5]

---

[1] The energy conversion in year No. 2 is used as representative for the yearly energy conversion.
[2] A time step of one hour corresponds to the time step of the weather data in the weather data file.
[3] Aperture area.
[4] The collector area is varied.
[5] Due to differences in the pit heat store geometry between the model and the real world the store height is calculated to give the same lid area.

4.6 Solar plant

4.6.1 Global

- T_forward = max(70 , T_forward_)[6]

4.6.2 Type109-TMY2[7]

- Ground reflectance = 0
- Slope of surface = collector_slope
- Azimuth of surface = 0°
- Weather data from AT-Graz-112400.tm2[8]

4.6.3 Shadow[9]

- Collector height = 2.27 m
- Collector row length = 200 m
- Collector slope = collector_slope
- Collector row separation = row_distance
- Number of rows = 100
- Collector array azimuth = 0°
- Slope of collector field = 0°

4.6.4 Collector-row[10]

- Number in series = 20
- Collector area = Area_one_string
- Intercept efficiency = eta_0
- Efficiency slope = a_1
- Efficiency curvature = a_2
- 1st-order IAM = 0.09
- 2nd-order IAM = 0

4.6.5 HX-1

- Heat exchanger effectiveness = 0.8[11]

---

[6] The forward and the return temperatures are coming from DH-load. The forward temperature is limited to not to be below 70°C.
[7] This component generates weather data, e.g. ambient temperature and radiation, based on data from a data file.
[8] Weather data are from Meteonorm.
[9] This component calculates the shadow effects in the collector field.
[10] This component calculates the useful energy gain in one collector row.
[11] Example: Balanced flow and T_{in} = 90°C/60°C gives $\varepsilon \cdot \Delta T$ = 24 K and T_{out} = 66°C/84°C.

4.7 Pit heat storage circuit

4.7.1 Pit-heat-storage[12]

- segments = 30
- Nflow = 4
- Joutj-1 = 30
- Joutj-2 = 1
- Joutj-3 = 15
- Joutj-4 = 1
- Volume = store_volume
- Height = store_height
- Top Depth = 0 m[13]
- Insulation Thickness = 0.7 m
- Top Fraction = 1
- Side Fraction = 0.5
- Bottom Fraction = 0[14]
- Insulation Conductivity = 0.360 kJ/hr.m.K

4.7.2 Shunt-1[15]

- Set point temperature = 90°C

4.7.3 Blow-Off[16]

- BlowOff_T_out = min(BlowOff_T_in , BlowOff_T_max)
- BlowOff_T_max = 80 [°C]

4.7.4 Shunt-2[17]

[12] This component is the XST model which is used to model the pit heat storage. The geometry of the XST model is cylindrical with vertical sides. This is different to the real-world pit heat storages with non-cylindrical geometry and sloped sides.
[13] The storage is not burried in the ground.
[14] No insulation in the bottom of the storage.
[15] To protect the lifetime of the liners in the storage this component ensures that the loading temperature never exceeds 90°C.
[16] To prevent boiling in the collectors this component blows heat off so the temperature to HX-1 never exceeds 80°C.
[17] To increase the performance of the collectors this component mixes the flow from the top and the middle diffusors in the storage to try to limit the temperature at Tee-2 to $T_{forward}$ + 5 K.

4.8 The district heating circuit

4.8.1 DH-load[18]

4.8.2 Heat-load[19]

4.8.3 Shunt-5[20]

4.8.4 Control[21]

4.8.5 HX-2

- Heat exchanger effectiveness = 0.85[22]

4.8.6 AHP-1[23]

- AHP1_Q_out_max_MW = 8.0 [MW][24]

4.8.7 Peak-load[25]

---

[18] This component reads data from the file Inputdata\Fernwärmedaten_Feldbach 2017.txt (see appendix D).
[19] This component calculates the mass flow in the district heating circuit based on data from DH-load.
[20] This component ensures that $T_{forward}$ is not exceeded.
[21] This component controls Valve-4 so HX-2 is used if the temperature in the top of the storage is > 75°C and AHP-1 is used if the temperature is < 70°C. Between 70°C and 75°C both are used.
[22] See the comment for HX-1.
[23] In this component the absorption heat pump is modelled. See appendix B for more details.
[24] The size of the heat pump is varied. It is noted that this is the AHP size for the solar/storage system not including extra capacity for cooling of flue gases.
[25] This component is a natural gas boiler which tops up the temperature from Tee-4 to $T_{forward}$.

4.9 Calculation of costs

4.9.1 Capital[26]

- Inv_collectors = 0.5e6 + 180 * Collector_area[27]
- Inv_pit = 1.5e6 + 15 * store_volume
- Inv_heatpump = 0.3e6 * AHP1_Q_out_max_MW**0.5
- Inv_tank = 0.05e6 + 100 * Tank_volume
- Investment = Inv_collectors + Inv_pit + Inv_heatpump + Inv_tank

4.9.2 Type24[28]

- Integration period = 8,760 hr

4.9.3 Operation[29]

- Cost_function = Investment / max(1 , Renewable_energy)
- Renewable_energy = Ope_hx2 + Ope_ahp_evap

[26] In this component the investments are calculated. See appendix C for more details.
[27] Aperture area.
[28] This component integrates (sums up) the energy conversion pr. year.
[29] In this component a cost function is defined. This can be used for numerical optimizations.

Appendix B – Modelling the absorption heat pump

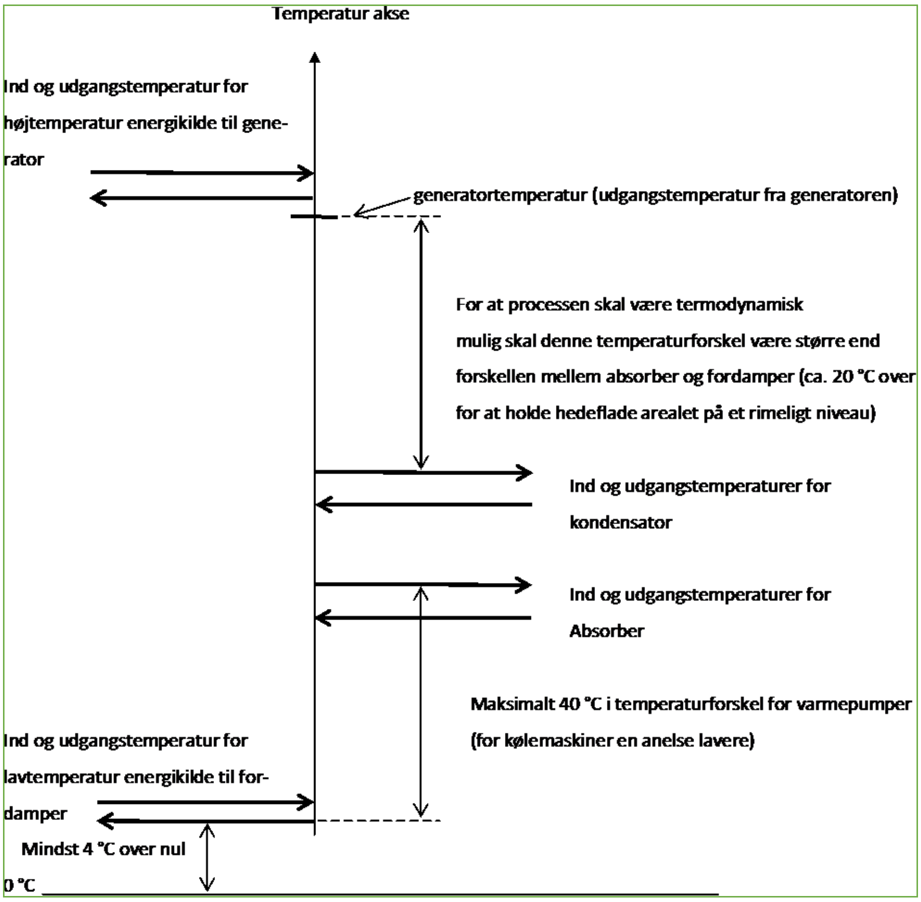

Figure B.1: *Temperature levels in an absorption heat pump.*
From S.E.G. A/S (http://segenergy.dk/wp-content/uploads/Absorptionsmaskiner.pdf).

Figure B.1 shows the temperature levels in an absorption heat pump with the evaporator in the bottom and the generator in the top. On the right-hand side the absorber is below the condenser. It is stated that the maximum temperature lift from $T_{evaporator,out}$ to $T_{absorber,out}$ is 40 K.

4.10 The heat pump model

Figure B.2 shows a principle diagram of the absorption heat pump. In real life the plant will consist of more than a single unit, and the units will be connected in parallel for the generators and in series for the evaporators. On the cooling side the absorbers will be connected in series, followed by the condensers. In the simulation the heat pump plant is considered as a single component.

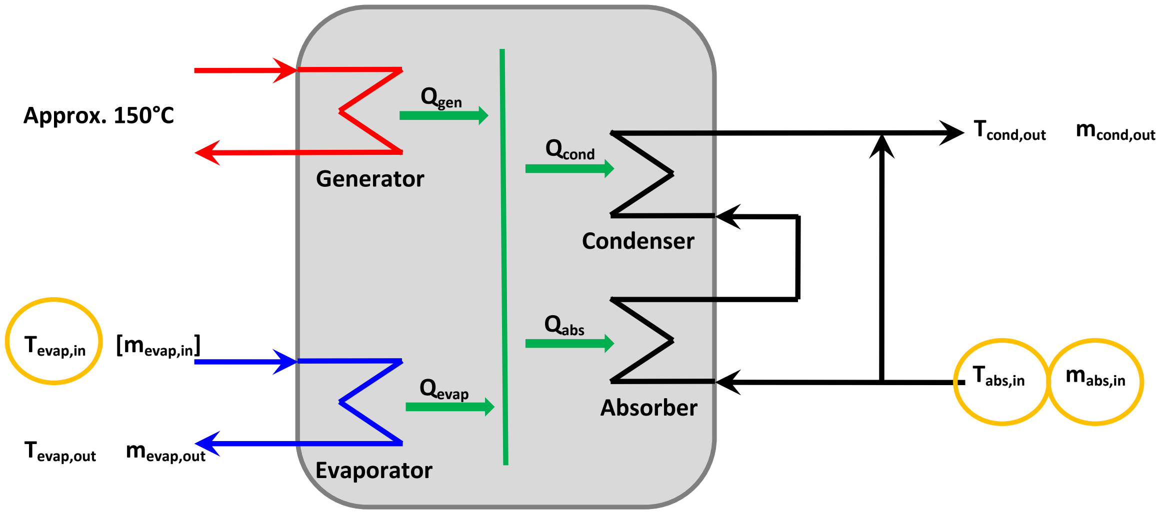

Figure B.2: *Principle diagram of the absorption heat pump.* ***T*** *are temperatures,* ***m*** *are mass flows and* ***Q*** *are heat flows.*

At the right-hand side of the figure a bypass is shown. This is used when the mass flow exceeds the heating capacity of the heat pump.

The inputs to the model are marked with yellow circles. $\mathbf{m}_{\mathbf{evap,in}}$ is not used as an input, but it is equal to $\mathbf{m}_{\mathbf{evap,out}}$.

It is assumed that the heat input to the generator is hot water at approx. 150°C, produced on natural gas boilers.

The main outputs are $\mathbf{T}_{\mathbf{evap,out}}$, $\mathbf{m}_{\mathbf{evap,out}}$, $\mathbf{T}_{\mathbf{cond,out}}$ and $\mathbf{m}_{\mathbf{cond,out}}$.

The main parameter in the model of the heat pump is Q_{out} which is the sum of the heat output through the absorber and the condenser ($Q_{out} = Q_{abs} + Q_{cond}$), which equals the heat input through the evaporator and the generator ($Q_{out} = Q_{evap} + Q_{gen}$).

The AHP-1 is modelled in the following way:

- $T_{evap,out} = T_{abs,\underline{in}} - 35$ K (based on figure B.1)
- $m_{evap,out}$ is calculated from $T_{evap,in}$, $T_{evap,out}$ and Q_{evap} (energy conservation)
- $T_{cond,out}$ is calculated from $T_{abs,in}$, $m_{abs,in}$ Q_{out} (energy conservation)
- $m_{cond,out} = m_{abs,in}$ (mass conservation)

- Q_{out} is not allowed to exceed the capacity of the heat pump (e.g. 100 MW).
- $T_{cond,out}$ is not allowed to exceed 90°C (based on figure B.1)
- The heat pump is bypassed when $T_{evap,in} < T_{abs,in} - 30$ K

- $Q_{evap} = Q_{out} * 76 / 176$ ($COP_{cooling} = 0.76$)
- $Q_{gen} = Q_{out} - Q_{evap}$ (energy conservation)

Appendix C – Estimating investments

4.11 Solar plants

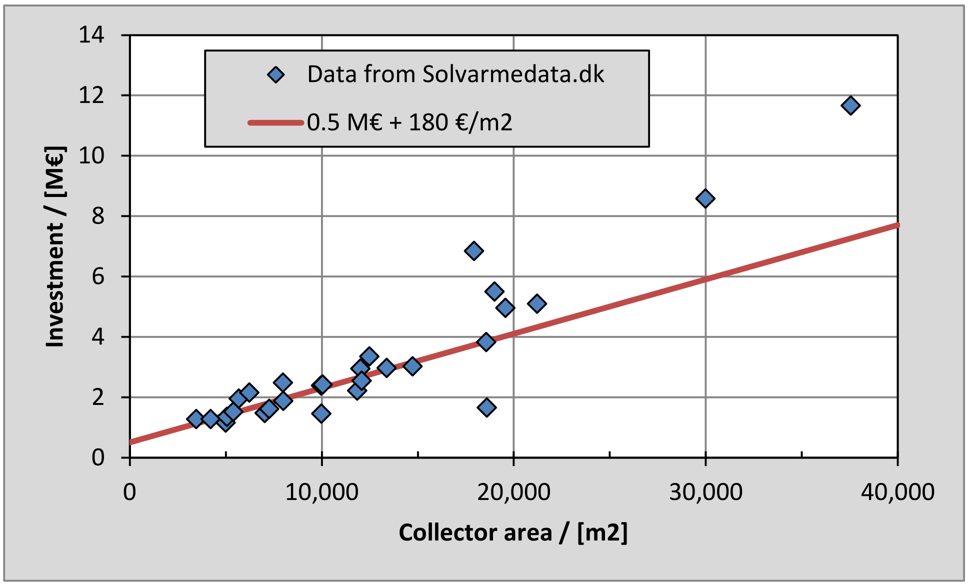

Figure C.1: *Realized investments from 28 Danish solar plants. Data from Solvarmedata.dk.*

Figure C.1 shows realized investments from 28 Danish solar plants.

The red trend line shows **<u>an initial investment of 0.5 M€</u>** plus **<u>a marginal investment of 180 €/m²</u>** **<u>aperture area</u>**.

The point at 30,000 m^2 represents Ringkøbing which, besides the 2 collector fields of 15,000 m^2 each, includes 2 heat accumulation steel tanks, 2 buildings and transmission lines.

The point at 37,500 m^2 represents Dronninglund which, besides the collector field, includes a 60,000 m^3 pit heat storage, a building and an approx. 3 km long transmission line.

4.12 Pit heat storages

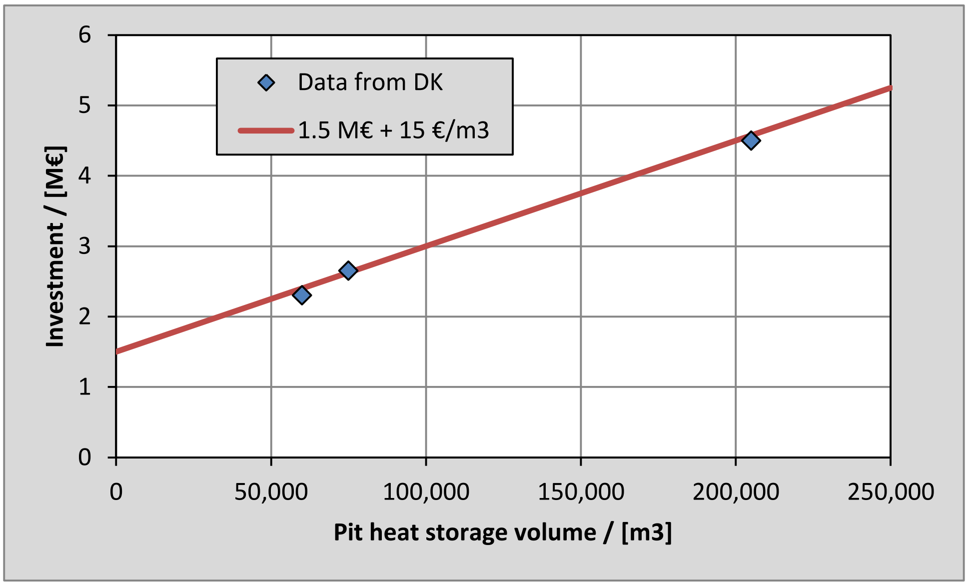

Figure C.2: *Realized investments from 3 Danish pit heat storages.*

Figure C.2 shows realized investments from 3 Danish pit heat storages.

The red trend line shows **an initial investment of 1.5 M€** plus **a marginal investment of 15 €/m^3**.

4.13 Absorption heat pumps

The investment in the absorption heat pumps is based on 3 price points from S.O.L.I.D. giving **an investment of 0.3 M€ * sqrt(AHP MW heat output)**.

4.14 Steel accumulation tanks

The investment in steel accumulation tanks is based on Danish experience as follows:

An initial investment of 0.05 M€ plus **a marginal investment of 100 €/m^3**.

Appendix D – DH temperatures and load