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Title:	Development of a single axis tracker for a hybrid solar system that can be integrated into building environments
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Summary

The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Portici has many activities related to solar power and one of these involves the development of concentrating solar power (CSP) systems. ENEA therefore started a program for the development of a hybrid photovoltaic and thermal concentrating system. The subject of this assignment was in line with this program to design a hybrid solar tracker that can be aesthetically integrated into building environments, has low production costs, a high optical efficiency and can easily be produced. This product must help ENEA getting a prominent position in the worldwide development of concentrating hybrid solar systems.

After a general orientation into CSP systems a study was done on how these systems work and are built up. The specific type of CSP system that was subject of this assignment uses a mirrored parabolic trough to reflect and concentrate solar radiation onto a receiver that converts the solar energy to electrical and thermal energy. By comparing different currently commercially available CSP systems for small-scale use, it became clear that this is only a small market, which focuses namely on efficiency and cost without paying attention to aesthetics. A cost breakdown of a comparable system showed the supporting structure, mirrors and receiver are the main components of the total costs. Small-scale use and the integration into building environments lead to a method to calculate the potential of a certain area so different locations can be compared for future fields of application.

A lot of stakeholders are involved in the area of sustainable energy. For example the European Union with the 20-20-20 targets which demands 20% of the European energy consumption to come from renewable resources by the year of 2020. The general preferences of the stakeholders together with the demands from ENEA were combined into the requirements. One of the most important requirements was to be able to apply the system on surfaces without permanent connection to the floor or rooftop. Wind loads become an important factor in this case and calculations have been made for a ballast compartment to withstand these loads. The functions the product must fulfill together with the influence of the wind loads acted as a frame in which three concepts were developed with a shift in priority between cost and aesthetics. With ENEA preferring to distinguish itself from competitors by aesthetically integrating the product into building environments, the concept with higher priority for aesthetics over costs was chosen to further develop.

The project resulted in a system with an integrated electromotor to track the sun during the day. Each module consists of a ballast part from PVC material that can be filled with sand to get the required weight to withstand wind loads. An aluminum structure supports the parabolic trough that consists of a mirror made from an aluminum sandwich structure, covered by an optional glass plate for protection of the mirror. To protect the system from extreme weather conditions the system rotates to a horizontal position so that the surface exposed to the wind is minimized. The supporting structure on the sides can be replaced by the same supporting part as is used in the middle to connect more modules in a long row. This makes the system modular because also the receiver can be connected by a coupling part. The power inverter that converts the direct current from the solar cells to alternating current limits the minimum (extra) field size. Eight modules, measuring 1.60 by 2.20 meters each, are needed for one power inverter to work efficiently. A field of this size yearly produces around 9600 kWh of thermal and 3500 kWh of electrical energy when exposed to a direct solar radiation of 1700 kWh/m^2 a year. In total an efficiency of approximately 48% is reached this way. Because the receiver is still to be developed by ENEA these estimations remain fairly rough, especially for the thermal part.

The final design fulfills almost all requirements. It depends however on the economic market whether the production methods for the different parts are appropriate because they are only suitable for a certain production number range. The system is also not fully plug and play, due to assembly actions that are still needed on the application sight and the needed coupling parts between the receivers for the modularity. The most important point of attention is the estimated price of 1500 euro's per stretching meter which is 25% higher than the competitors. The final product has a comparable performance but aesthetically distinguishes itself from other systems, without the need to adjust the application surface. In the future development optimization of parts to lower the costs will be a major aspect. Also in this stage the receiver has to be developed so that better estimations on costs and performance can be made. To make the system more flexible, alternative solutions have to be found for the currently used power inverter that limits the minimum (extra) field size. The system's potential to satisfy the demands of the European Union is high by applying the product to appropriate buildings.

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1. Preface

The reason for this report to be written is to complete the Bachelor phase of my study as an Industrial Design Engineer. For this assignment, which takes three months, it is possible to get some experience in a foreign country and I preferred to go to Italy. I would like to thank Angele to give me the option to go to ENEA. As my University tutor I was lucky to have her on the same location for the first two months. We had a lot of discussions on the cultural differences between Italy and The Netherlands but she also gave me advice about the assignment.

Furthermore I would like to thank my first company supervisor Carmine for helping me out with so many questions and for unintentionally pushing me to speak Italian. It was really interesting to work with a dedicated engineer that not only prefers carbon steel but also Baba. Special thanks to Maria for helping me with the FEM analysis and being so enthusiastic to help me out. I liked figuring out together what was wrong and give a ‘cinque alto’ when it worked.

Gli altri studenti alla 'camera oscura' mi hanno aiutato con la mia lingua Italiana e voi sono stati partner grande di pranzo. Avete avuto grande pazienza con me e vi auguro Diego, Giuseppe e Romina in boco al lupo (crepi) con il loro grado. Spero per Giuseppe la bambina non si sveglia tropo e hai abbastanza riposo, mi sono divertito la tua visione e i tuoi scherzi molto. Un periodo di riposo si auguro anche Ricardo che ha appena sposato, in boco al lupo con tutto ciò, tu sei stato sempre gentile, non importa quello che è successo. Anche Valerio e Silvia grazie tante per avermi aiutato a pianificare i miei viaggi per l'Italia. E per ultimo ma non meno da ENEA Paolo, Maria, Domenico, Silvio, Ettore, Giorgio, Valerio, Felice e Enzo eravate buoni partner per parlare di calcio, cultura, lavoro e altre cose tipicamente Italiane come caffè. Mi piaceva tanto per conoscere voi tutti.

And finally my second supervisor and help and support Alessandra, thank you for everything. You gave me great memories. You were so kind and helpful, not only at ENEA when I couldn’t figure something out and you still managed to make me smile, but also for telling me about all interesting and must-see places in and around Naples. I wish you good luck with the final weeks before your PhD degree and would love to see you again in Naples or maybe Palermo.

Reinier ter Welle

2. Introduction

The research of this project is done at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). ENEA's activities are targeted to research, innovation technology and advanced services in the fields of energy and sustainable economic development. The specific research centre of ENEA in this case is the Portici Research Center, which among others focuses on the development of concentrating solar power (CSP) systems and therefore started a program for the development of hybrid photovoltaic and thermal concentrating system. Such a system is able to produce electrical and thermal energy. The subject of this assignment was to design a single axis hybrid solar tracker that can be aesthetically integrated into building environments, has low production costs, a high optical efficiency and can easily be produced. This product must help ENEA getting a prominent position in the development of concentrating hybrid solar systems.

After an analyzing phase and the gathering of the requirements some concepts are developed. The best aspects of these concepts are combined and then further developed into a final design proposal in the form of a digital model. In this report this chronological construction is kept. Chapter 3 and 4 describe the different types of CSP systems and how they work. The 5^{th} chapter compares different solar systems to get an overview on the development and current market. A cost component breakdown of this type of products is done in chapter 6. The next chapter describes the most important stakeholders in the lifecycle of the solar concentrator with their general requirements. The current and potential fields of application can be seen in chapter 8. Here also a method is shown to calculate the potential of an area to apply solar concentrating systems. In chapter 9 the requirements from the analyzing phase together with the requirements that came to light during the design process are named. The last two chapters of the analyzing phase contain the functions the product must fulfill in chapter 10 and the calculation of some dimensions as a result of wind loads in chapter 11, needed for the development of concepts.

In the concept phase three concepts are described. Each of them combines different solutions from sub-problems that are made via so called morphological schemes. These scheme are used to find solutions to sub-problems and some of them are shown in the beginning of chapter 12. The choice of solutions from the concepts is done in chapter 13. After that the final design is described in chapter 14 that outlines all the different components in detail. Also choices of material, assembly and production methods are described. In the last part of this chapter the estimated costs and energy production are shown and also some renders can be found here.

Finally the conclusion and recommendations are described in chapter 15. In the conclusion the final design is compared to the requirements and to competitors from the analyzing phase. The recommendations outline the subjects that need more attention before the product reaches a mature development status. Appendices with datasheets, reports from the FEM analysis and the initial project plan can be found after the references.

3. Concentrating solar power systems

Concentrating solar power (CSP) systems use lenses or mirrors to focus a large area of direct sunlight onto a small area. By concentrating the sunlight on a small area, expensive photovoltaic (PV) cells and thermal absorbers can partly be replaced by cheaper mirror area, thereby saving costs and reduce the payback time. This argument is the driving force behind concentrating solar power systems. For this aim, it is necessary to develop specific components, such as a concentrator module and tracking structure, able to benefit from the advantages of the solar concentration.

There are some different types of CSP systems. In a concentrated solar thermal (CST) system, concentrated sunlight is used to heat air or a fluid which can be used as an energy source, or for hot water for domestic use for example. A concentrated photovoltaic (CPV) system on the other hand, employs the concentrated sunlight onto a photovoltaic surface for the purpose of electrical power production. And last, a concentrating photovoltaic and thermal (CPVT) system, combines these two types of systems by using the heat generated in the photovoltaic (PV) cells to generate not only electrical, but also thermal energy simultaneously.

A CSP system is only useful under direct sunlight; therefore a solar tracker is needed for orienting a concentrating solar reflector or lens towards the sun.* This way, the focus of the sunlight does not move outside of the area where the receiver of the radiation is placed. Compared to a fixed solar system, more power can be generated at the cost of additional system complexity.

There are many types of solar trackers, of varying costs, sophistication, and performance. The major differences are between the amount of axes, the type of tracking and the form of the concentrating mirror. A single axis solar concentrator rotates in the altitude direction from east to west. The axis can be horizontally placed or have a manual elevation (axis tilt) adjustment on a second axis which is adjusted on regular intervals throughout the year. A dual axis tracker adapts to these conditions automatically by also having a vertical axis that follows the difference in heights of the sun.

Figure 1 Single axis parabolic trough CSP system (Quaschning, 2010)

Figure 2 Dual axis parabolic dish CSP system (Quaschning, 2010)

The information for getting the position of the sun can be extracted by sensors, GPS or a combination of these two. Sensors have the least accuracy especially when it's cloudy for some time, whereas GPS uses programmed software for the location of the sun, therefore being more precise in overall performance. To check the GPS coordination's by a sensor makes the system the most accurate by taking into account movements from the structure.

* N.B. In the rest of the report only DNI (Direct Normal Irradiance) values will be used for the solar radiation.

The last aspect that makes a major difference between CSP systems is the form of the mirror. Besides the parabolic trough and parabolic dish systems shown in the figures before, also a solar power tower and linear Fresnel reflector are sometimes used.

Figure 3 Linear Fresnel reflector CSP system (HelioDynamics, 2010)

Figure 4 Solar power tower CSP system (BrightSourceEnergy, 2008)

The type of CSP and tracking system for this project is a CPVT, which uses a mirror in the form of a parabolic trough to concentrate the sunlight. The system uses a horizontal single axis tracker. That means it has only one degree of freedom; it rotates around a horizontal axis of support called the altitude axis.

4. Concentrating photovoltaic thermal system – parts and working

The few CPVT systems commercially available on the market consist of different parts that are listed here (see also Figure 5);

- Parabolic mirrors
- Receiver (including PV cells and thermal receiver)
- System control
- Supporting frame
- Roof or ground mounting
- Tracking mechanism with actuators
- Water storage
- Power conditioning
- Electrical and plumbing installation
- Heat dump radiator (to shed any excess energy)

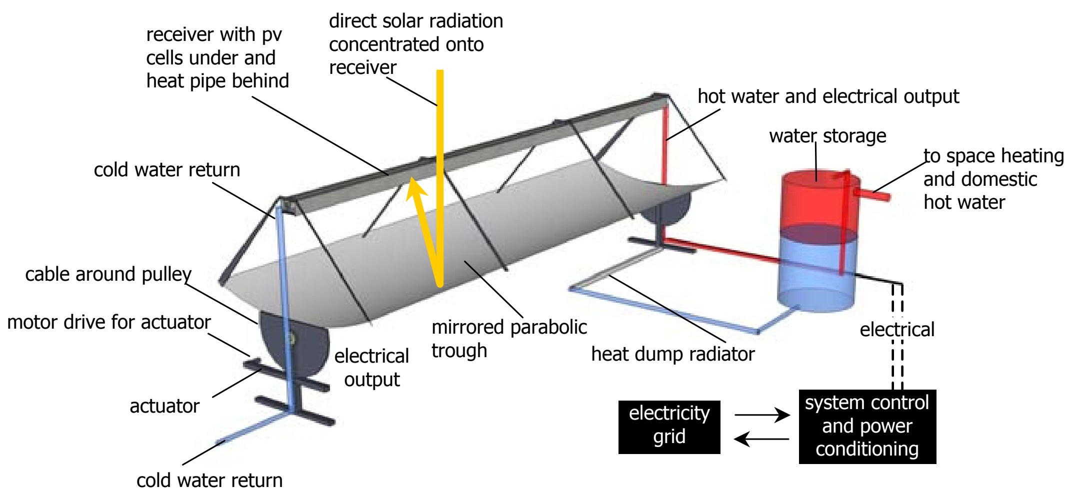


Figure 5 Different parts of CPVT system (Barton, 2009)

The mirrored parabolic trough as a whole will reflect direct sunlight along one axis, the focus. In this focus, a receiver is placed with PV cells. These are made of special materials called semiconductors such as silicon, which is currently used most commonly (HowStuffWorks, 2010). Basically, when light strikes the cell, a certain portion of the radiation is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. PV cells also have one or more electric fields that act to the force electrons, freed by light absorption, to flow in a certain direction. This flow of electrons is a current, and by placing metal contacts on the top and bottom of the PV cell, it's possible to draw that current off for external use. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power (or wattage) that the solar cell can produce. This direct current (D.C.) is inverted by a power conditioning/inverter into alternating current (A.C.), so it can be directly used or added tot the electricity grid. A special control system heads al the electricity flows.

A large part of the energy from the sunlight in the PV cells is not converted into electric current but into heat. Here the thermal collector comes to use (for a detailed close-up, see Figure 6). Although the thermal part of the receiver is heated via solar radiation, it also cools the PV cells to keep them efficient. This cooling function happens by conduction through materials and convection through a moving flow of fluid, where the heat is transferred into the thermal receiver. The fluid can be simple water or a molten salt for example, depending on its purpose. A larger heat supply system contains thermal storage and piping to store and transfer the hot fluid. To shed any excess energy from the hot fluid a heat dump radiator can be used; this is an extra loop in the system that transfers the energy into the open air.

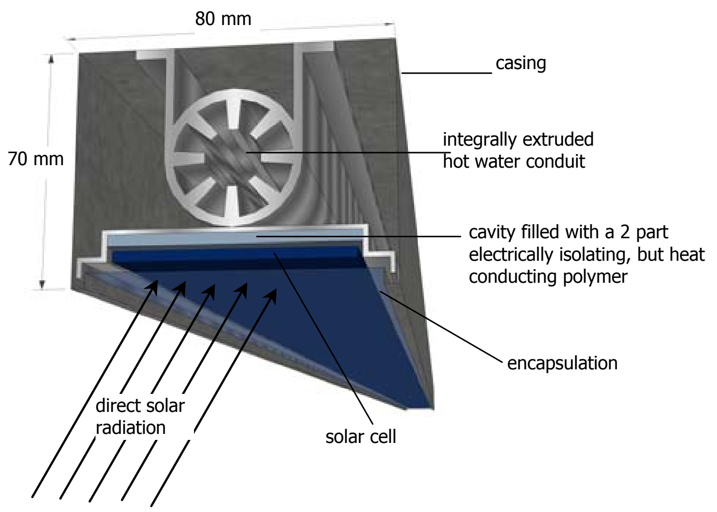


Figure 6 Close up of receiver (Barton, 2009)

A schematic representation of such a CPVT system is given in Figure 7, including the functions of the different components displayed in yellow rectangles. These functions where also derived from the information given in the chapters 7-9. The blue arrows indicate water flows (hot and cold), the red arrows indicate electrical flows.

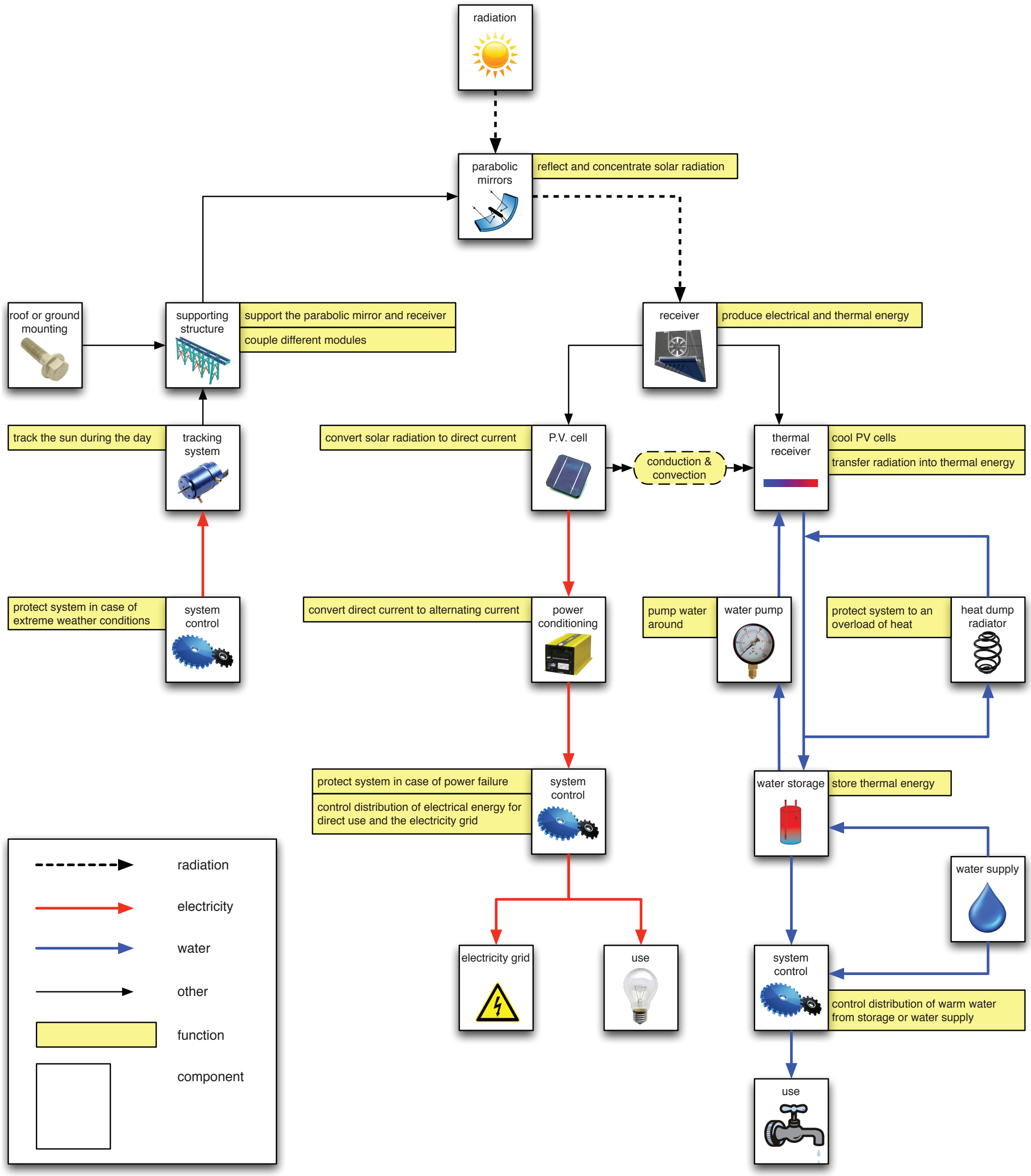


Figure 7 Function diagram of a CPVT system

5. Comparing different solar power systems

Because there are many different types of solar power systems (Flat Panel PV, CPV, CST, CPVT etc.) and each type has it's own cost pattern, features, technical design, field of application and so on, it's hard to compare the systems directly. The search for the best solar power system also depends on the type of project for which a solar power system is sought, which makes it even more difficult. ENEA at this moment has not yet designed a CPVT system and therefore the CST system from the Archimede project ENEA is currently running with ENEL, will be used in the comparison instead. Before making a competitor analysis there are a few terms to be introduced. After that in Figure 8 different types of CSP systems are compared with number of specifications.

5.1 Levelized cost of energy

An important factor is the costs of different types of solar systems. To make this aspect comparable the term 'levelized cost of energy' (LCOE) is introduced. The LCOE equation is one analytical tool that can be used to compare alternative technologies when different scales of operation, investment or operating time periods exist. The calculation for the LCOE is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life (Campbell, 2008).

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}} \tag{1}$$

The end result will be in the form of a currency per kWh, $/kWh for example. The major inputs for the calculation of the LCOE are:

- Initial investment
  - Area-related costs
  - Grid interconnection costs
  - Project-related costs
- Depreciation tax benefit (the present value of the depreciation tax benefit over the financed life of the project asset)
- Annual costs (maintenance, cleaning, insurance, repairs etc.)
- System residual value
- System energy production

Because the calculation of LCOE is highly sensitive to installed system cost, O&M costs, location, orientation, financing and policy, it is not surprising that estimates of LCOE vary widely across sources. One recent source estimates that worldwide, the range of LCOE is approximately $0.20–$0.80 per kWh for rooftop PV and $0.12–$0.18 per kWh for parabolic trough CSP power plants, not including government incentives (REN21, 2008). In many cases the LCOE isn't even known because the system are not yet (commercially) applied or tested yet.

5.2 Peak power

The electric characteristics of solar cells vary with respect to various general conditions, especially the radiation intensity. In photovoltaic's, the maximum possible output of a solar generator operating under standard conditions is defined as its peak output, which is measured in watts or kilowatts and stated as either watt peak (Wp) or kilowatt peak (kWp), respectively. An optimal solar radiation of 1000 W/m^2 is defined as the standard condition, and it can be reached early afternoon on a sunny summer day. The peak output is so based on measurements under optimal conditions. The mean output however over the period of a year is only about one tenth of the peak output due to nighttime and less than optimal daytime sun conditions (Solarserver, 2010).

5.3 Solar radiance and annual production

Solar radiance is the amount of incoming solar electromagnetic radiation per unit area that would be incident on a plane perpendicular to the rays, at a distance of one astronomical unit (AU) from the source. This distance is roughly the mean distance from the sun to the earth. The solar constant includes all types of solar radiation and is measured by satellite to be around 1.367 kilowatt per square meter (kW/m^2) as a world wide average (Pidwimy, 2010). The weather and the location are aspects that influence the annual average of solar radiation. To compare different solar systems it is important to know how much radiation could be received on average. That’s why in this case it is easier to compare the systems by the total radiation during a year in $kWh/m^2/y$, while the energy production of the CSP’s are also often measured in this unit. From these two aspects the efficiency can be calculated.

5.4 Overview

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
General information														
Manufacturer	Absolicon	Power-Spar	SEGS 1	SEGS 9	ANU	Solargenix Energy	Solar Millennium	SkyFuel	Heliodynamics	ENEA/ENEL	Alcoa	Abengoa	Wattsun	Array Technologies
Country	Sweden	Canada	Israël	Israël	Australia	U.S.A.	Germany	U.S.A.	U.K.	Italy	U.S.A.	Spain	U.S.A.	U.S.A.
Product name	X10	PS-35	SEGS 1	SEGS 9	CHAPS	Nevada Solar One	Andasol 1	SkyTrough	HD10	Archimede	-	RMT	AZ-225	DuraTrack HZ
System type	CPVT	CPVT	CST	CST	CST	CST	CST	CST	CST	CST	CST	CST	PV	PV
	Parabolic trough	Power tower	Parabolic trough Power plant	Parabolic trough Power plant	Parabolic trough (Demo)	Parabolic trough Power plant	Parabolic trough Power plant	Parabolic trough	Linear Fresnel	Parabolic trough Power plant	Parabolic trough (Test fase)	Parabolic trough (Under dev.)	Flat panel Sanyo PV's	Flat panel (Suntech Reliathon)
Year of introduction	2007	NA	1985	1991	2006	2007	2009	2009	2009	2011	2013	2013	2008	2010 (Q2)
Performance														
LCOE ($/kWh)	NA	NA	0.45	0.18	NA	0.18	0.36	0.07-0.11	0.08-0.18	0.06	NA	NA	0.09	NA
Peak power (Wp)	550	6500	-	-	-	-	-	-	-	-	-	-	3000	NA
Electrical energy (kWh/m²/y)	120	270	-	-	-	-	-	-	-	-	-	-	250	NA
Thermal energy (kWh/m²/y)	750	560	200	260	150	520	310	420	380	290	NA	NA	-	-
Solar radiance (kWh/m²/y)	1800	1800	2700	2700	1600	2600	2200	2300	2500	1900	NA	1600	2200	NA
Efficiency *	48%	46%	7%	10%	9%	20%	14%	18%	15%	15%	NA	20%	11%	NA (only tracker)
Technical aspects														
Dimensions per unit (wxd) (m)	1.1 x 6	7.3 x 6.8	NA	NA	1.5 x 24	4.7 x 100	6 x 12	6 x 115	4 x 6	5.9 x 12.5	6 x 14	1.1 x 3.7	4.5 x 4.5	NA
Weight per unit (kg)	195	1600	NA	NA	NA	NA	NA	NA	380	NA	NA	30	NA	NA
Tracking system														
Solar tracker type	Single axis	Dual axis	Single axis	Single axis	Single axis	Single axis	Single axis	Single axis	Single axis	Single axis	Single axis	Single axis	Dual axis	Single axis
Tracking of sun by	GPS	NA	Sensors	Sensors	GPS	Sensors	Sensors	NA	NA	GPS	NA	GPS	Sensors	GPS
Accuracy	NA	NA	NA	NA	NA	NA	NA	+/- 0.06°	NA	NA	NA	NA	NA	+/- 2°
Other														
Mirror material	Aluminium	NA	Glazed	Glazed	Glazed	Glazed	Glazed	ReflechTech	Glazed	Glazed	Aluminium	Glazed	-	-
Cooling type	Fluid	Fluid	Fluid Therminol VP-1	Fluid Therminol VP-1	Fluid Water	Fluid Dowtherm A	Fluid Di/Bi-phenyl Oxide	Fluid Therminol VP-1	Fluid	Fluid Molten salt	Fluid	Fluid	Air	Air

* Average annual efficiency (look carefull at solar irradiance, system type and introduction year)

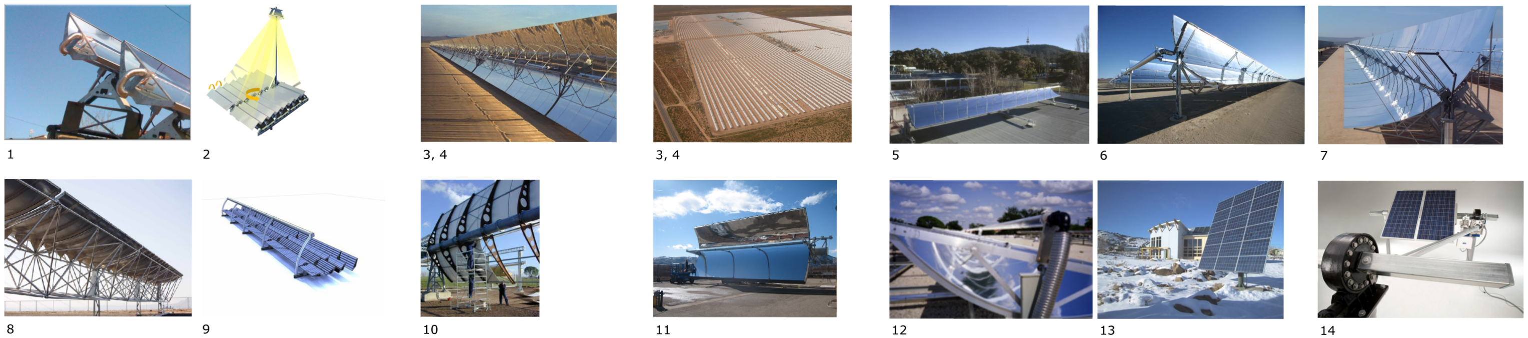


Figure 8 Comparison of different solar systems (for references see 'References – Figure 8')

5.5 Trend in efficiency and costs

From Figure 8 a few things can be seen. Three types of systems are compared, from which the CPVT systems are only recently been put on the market. CST systems were also made two decades ago in the form of large solar plants. Only in this form the LCOE could be sufficiently low to compete with other forms of energy sources. Between 1995 and 2005 no parabolic trough power plants were built in the U.S.A. for example. A number of factors contributed to the lack of any new parabolic trough power plants construction during this period. Because of declining federal and state incentives combined with declining energy prices, parabolic trough power plants were no longer economically competitive with conventional power plants. These factors combined with a general move to deregulation of the power industry, which focused on least-cost power options, precluded any new large solar plant developments (NREL, 2008).

The LCOE between the SEGS 1 en 9 shows a large improvement but the rest of the systems differ in such way, that no direct conclusions can be made. However, if we compare the LCOE from different energy sources, it clearly shows solar power is the most expensive energy source (Figure 9). A target LCOE of about $0.10 must be obtained on the long term, which is less than half of the average price right now.

An interesting fact is the large increase in efficiency of a single-axis CPVT compared to a dual-axis flat panel CPV, which shows the great potential these system may have. From the table increase in efficiency (on average) over the years of all systems can be extracted, with the demo CHAPS system as an exception. Recent activities over the last five years like the CHAPS and Absolicon systems show that small-scale commercially attractive CPVT and CST systems can be made in the near future.

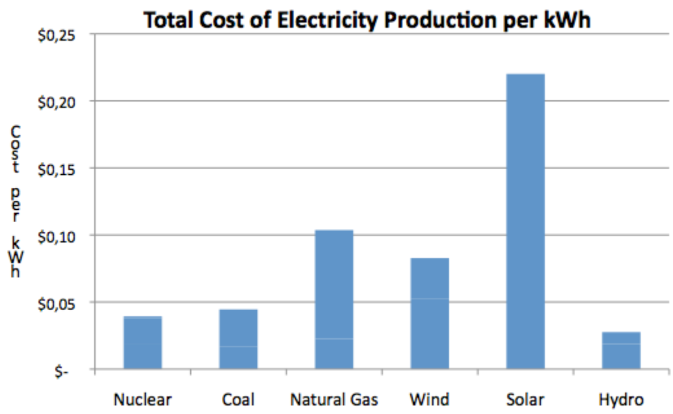


Figure 9 Costs per kWh for different energy sources (Morgan, 2010)

5.6 Visual aspects

Most of the work in the development of CSP systems has been focusing on the performance. For a large power plant the priority of the visual aspects is understandably low. Before small-scale energy production systems for residential use can be placed in an urban environment, the performance must be profitable. From that moment on, the visual aspects begin play a more important role. Looking at some of the existing systems, parabolic troughs look al a bit similar because of the parabolic shape and reflective mirror material. This is however not the most important part from the visual point of view, because of two reasons. First, there's not much freedom left to redesign the parabolic mirror and second, when applied on top off buildings, the sides and bottom side are mostly seen whereas the mirror is aimed at the sun. In the following figure a few designs are highlighted.

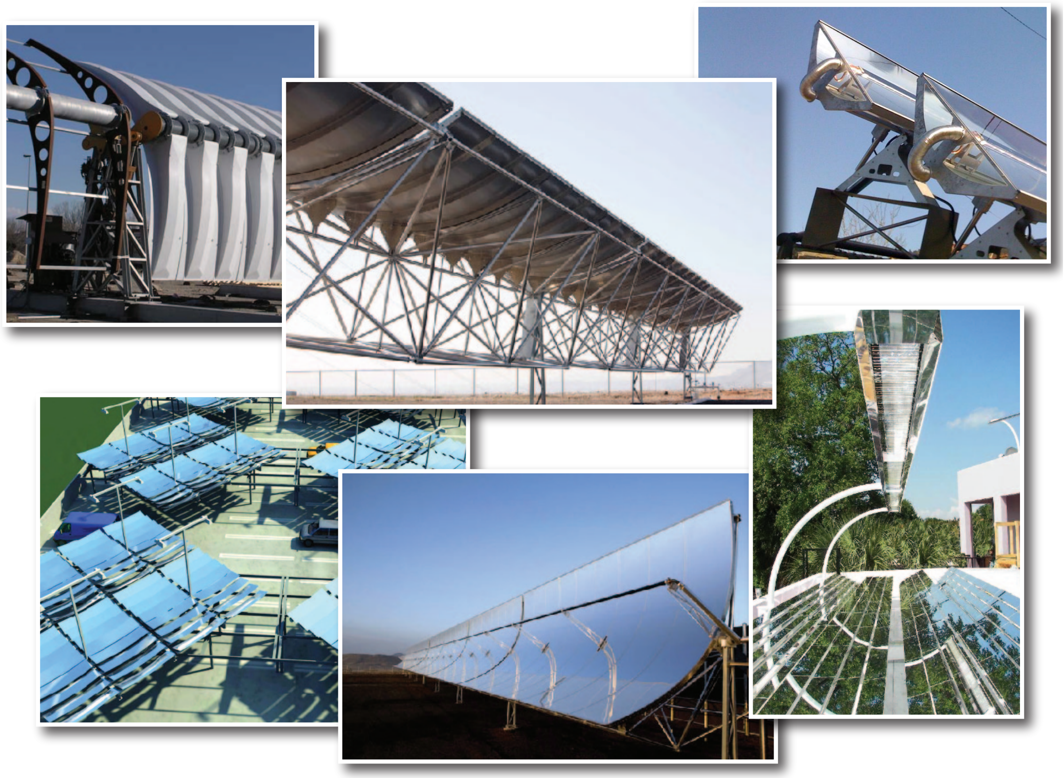


Figure 10 Examples of concentrating solar system designs (Maccari, 2006) (Skyfuel, 2010) (Absolicon, 2010) (WSP, 2009) (Eco Building Club, 2009)

As you can see the bottom structure has a mechanical look and the structure is very functional. The form-follows-function principle is well applied, maybe without the designers even being aware of this. Also the thermal piping passes clearly outside the parabolic trough. The linear Fresnel type from Power-Spar (the lower left picture) has only the receiver sticking outside of the flat mirror part, but this makes the system also less effective. By taking the visual aspects into account from the beginning of the design process, these systems can be made aesthetically more attractive.

6. Cost components breakdown

To design a low cost single axis tracker for a CPVT system, an analysis must be first made of the cost components of the existing product. Such detailed information is not yet available for CPVT systems so a similar CST system will be used as s basis for this part. For parabolic troughs (SEGS), the cost breakdown is shown in the next figure.

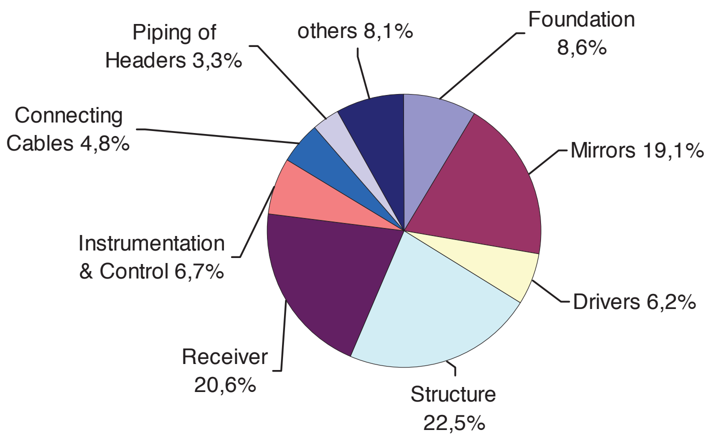


Figure 11 Cost breakdown of CST SEGS system (Pitz-Paal, 2005)

As the receiver is part of the trough, the structure (22.5%) and the mirrors (19.1%) are the main cost-intensive components of trough systems. From this information it can't be directly derived the biggest potential for cost reduction are the structure (incl. tracking system) and mirrors, but it gives an indication that a combination of receiver, mirror and supporting structure could have a big influence on the price of CST systems when made cheaper.

Another figure from a paper by NREL shows the importance of five major cost components that contribute to the LCOE of the example CST system (Figure 12). Again, the concentrator structure, mirror en receiver (Heat Collecting Element) influence the LCOE for a major part, but also the storage of heated fluid has a large share now. The power block can be neglected because this converts the heat from the fluid via a turbine intro electricity, which in a CPVT system will be directly done through the PV cells.

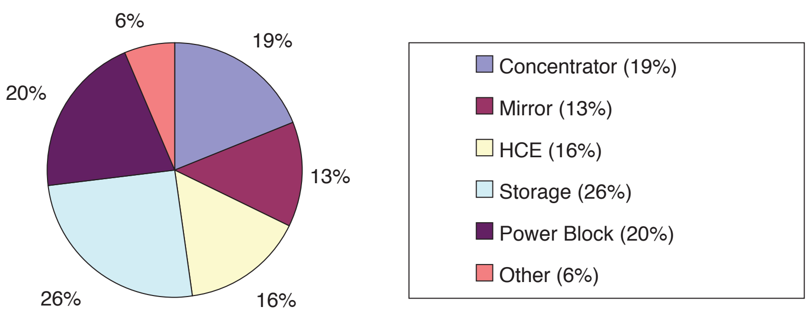


Figure 12 Major cost components CST system (NREL, 2003)

Production, assembly and operating and maintenance (O&M) costs are spread onto these major cost components. The contribution from the O&M costs to the total LCOE is expected to be about 15% (NREL, 2003), for a large power plant that has a permanent staff. It should be noted that many aspects influence these numbers; it depends for example on the scale of production, O&M contracts with independent companies, future incentives from governments, differences in annual energy production, location etc. That's why in this stage of development it is hard to say what the expected contribution of production, assembly and O&M costs of residential CPVT systems will be.

7. Fields of application

7.1 Current fields of application

Concentrating solar power is a technique that is known for a long time. The first application in the current form as an energy source goes back to 1984 when first SEGS solar plant was built. In the following years only large-scale applications where built in numerous power plants (Figure 13). Because the energy is first stored before it is used, high efficiencies where desirable and therefore high temperatures of 150-550°C are used (Archimede Solar Energy, 2010).

Figure 13 SEGS III power plant (Californiaphoton, 2008)

Figure 14 ANU CHAPS system (Barton, 2009)

7.2 Potential fields of application

Small-scale commercial parabolic trough concentrators where not introduced until a few years ago. Because of technical development and the demand for sustainable energy sources parabolic trough systems for small-scale use are now becoming an interesting option. The demo from the Australian National University is a good example of this small-scale use (Figure 14). Because of the direct use of the energy for domestic application the featured temperatures (<100°C) are relatively low compared to power plants (Coventry, 2003). Applying CPVT systems in building environments requires detailed knowledge about the location where the system has to be installed. The most interesting option is to look at cities, because of the high concentration of buildings and the large energy demand. As one of the requirements from ENEA is to have no permanent attachment to the surface where the solar concentrator is applied to, flat surfaces are the best option because a uniform system on pitched roofs would become very complex. This flat surface can be on the ground or on flat roofs for example, but you can imagine a certain amount altitude is required because of shadowing reasons. The structure of the city or a certain district is strongly defining the potential for CPVT systems. To cite all the possible aspects that affect the potential of a certain area for the appliance of a CPVT system, a formula is given on the next page to calculate this potential. This formula can be used for electrical or for thermal energy.

$$\text{Potential} = \frac{\text{Energy production}}{\text{Energy use}}$$

$$= \frac{R \times E_{t/e} \times A_{tot} \times A_{factor}}{P \times U_{t/e}}$$

where $A_{factor} = A_{flat} \times A_{useable} \times A_{CPVT}$

$$P = \rho_{person} \times A_{tot} \qquad (2)$$

R = radiation in $kWh/m^2/y$

$E_{t/e}$ = thermal or electrical efficiëncy CPVT

A_{tot} = area of district in m^2

A_{flat} = area factor flat roof

$A_{useable}$ = area factor useable roof

A_{CPVT} = area factor CPVT regarding avoidance of shadowing

ρ_{person} = people density in city in $persons/m^2$

$U_{t/e}$ = average energy use in kWh/y

The energy production of the CPVT systems divided by the energy use of an area is the potential and will lie between 0 as a minimum and 1 as a maximum. In the latter case, all the energy needed can be produced by placing CPVT systems in that area. Important factors are the solar radiation in the area and the area factor. Appropriate site locations for CSP systems in general are located in 'solar belt' within 40° latitude north and south because of the higher radiation close to the equator (Fernández-García, 2010).

In the equation the area factor includes many sub-factors that diminish the total energy produced. All these sub-factors are less than one. The area factor of flat roof assumes that the CPVT systems are placed on roofs or flat areas and not on the ground for example. The factor for useable area on these roofs compensates for architectural reasons (chimneys, antennas, shadowing from tall buildings etc.) and is usually around 0.45 (Barker, 2001). The CPVT factor compensates for the fact that parabolic trough are placed at a certain distance from each other, the so called pitch, to avoid shadowing from one to another. For the energy use the total amount of people can be used for small areas multiplied by the average energy use. For larger sites the city density of people may also be appropriate.

To give an example on how much the city and district can influence the potential fields of application a small area of two cities in Italy are shown, pictured at the same altitude measured from the ground (Figure 15 and Figure 16). In Naples the higher contrast between streets and building roofs indicate that the average building is higher than in Palermo. This means more energy use per square meter, while there's less flat roof surface available per person. The urban roughness defines to what extent the buildings shadow each other and is more or less the same for both cities. Although the roof colors are different this should not be confused with shadowing. For the total district Naples has more possibilities to apply solar systems but Palermo on the other hand has higher solar radiation per year. To calculate the electrical potential equation 2 is used with the factors from Table 1, derived from more detailed pictures of these districts.

Figure 15 Naples (Google Earth, 2010)

Figure 16 Palermo (Google Earth, 2010)

	Naples	Palermo
radiation	1700 kWh/y	1900 kWh/y
electrical efficiency *	12.8%	12.8%
area of district	$1 \cdot 10^6$ m^2	$1 \cdot 10^6$ m^2
area factor flat roof	70%	45%
area factor usable roof	0.45	0.45
CPVT shadowing factor **	0.40	0.40
people density ***	8200 per $1 \cdot 10^6$ m^2	4100 per $1 \cdot 10^6$ m^2
average energy use ***	5420 kWh	5420 kWh

* see chapter 15.11 Energy production
** see chapter 15.1 Optimum pitch
*** CIA, 2010
Table 1 Factors to calculate the district's electrical potential of applying CPVT systems

The potential of the solar concentrator for electricity use for Naples in this case is 62%, as for Palermo this is 89%. Although the area factor of Naples is much higher, it can not compensate the difference in people density. This makes Palermo the city with more flat roof area per person which contributes together with the higher radiation to a higher potential. The same formula can be applied for thermal energy.

In general because of the amount of flat roofs and solar radiation, cities in the Mediterranean area have the highest potential for CPVT systems. Also Santa Fe and the Higher Dessert neighborhood in Albuquerque in the United States are good examples of areas with high solar radiation and much flat roof area per square meter (LoneMountain, 2010). Furthermore, a north–south orientation of the parabolic troughs (lengthwise) maximizes the amount of power produced along the year (Fernández-García, 2010). Examples of possible specific buildings to apply the system are parking structures, hotels, houses, apartment complexes, stations and office buildings.

8. Stakeholders

In the whole process from research until demolition there are a lot of stakeholders involved, all with their own preferences and requirements. To give insight in these parties with some of their main characteristics the following figure is given, partly derived from the information given in the PVT Roadmap (Zondag, 2006). One important stakeholder is the European Commission with the 20-20-20 targets which demands 20% of the energy consumption to come from renewable resources by the year of 2020 (European Commission, 2007).

Party	Factors	General requirements
National governments	Kyoto agreement (not U.S.A.) E.U. law and targets Promotional Specify regulations Direct and indirect subsidies Energy performance building directive Energy prices	Development of sustainable energy sources More energy consumption to come from renewable resources Reliable systems R&D activities on CPVT Mentality change of all parties involved Low interest funding
Installers	Experience in installing National government policies Similarity between different systems	Knowledge for advising Rigid system Easy to mount (same or less skills required compared to other solar energy systems) Plug-and-play system Profitable systems
Architects	Building integration Acceptance Criteria from municipal authorities Criteria from national government	Flexible system in shape Aesthetically attractive products Added value that helps selling or promoting Easy to implement Profitable systems
Municipalities	Motivating private people Fulfillment of obligations Profiling municipality	Expertise on subject Reduction of project management and planning Standardization to measure performance
Energy companies	Diminishing peak demands Promotional Criteria from national government Competitors	Temporary energy storage Reduce total investment of energy production
Homeowners	Energy prices Lifestyle Image Acceptance	Aesthetically attractive Profitable systems Comparison from consumers organisation Good after sales service Easy handling and maintenance
Farmers	Floor heating Food preparation Criteria from municipal authorities Criteria from national government	Hot air and water Profitable systems
Real estate developers	Criteria from municipal authorities Criteria from national government Selling of houses (promotional) Energy prices	Certain energy performance Cost effective Green image High feed-in tariffs
Housing associations	Privatisation of market Promotional National government Municipality	Profitable systems Short payback time Reliable systems Reduction of project management and planning Sufficient area use Compensation for investment somehow
Financial sector	National government Green funds	Short payback time CPVT part of mortgage High interest funding
R&D sector	National government	Subsidies for R&D
Energy consultancy companies	Promotional Improve market position	High profile technique Knowledge for advising
CPVT manufacturers	Feedstock supply National government Portfolio Quality demands	Fast and cheap quality process High feed-in tariffs
(Governmental) Real estate owners	Solar percentage targets Promotional	High feed-in tariffs Profitable systems
Foundations (hospitals, homes for elderly)	Costs Continuous electricity demand	Save on water heating and electricity costs Back-up system in case of breakdown

Figure 17 Overview of stakeholders and their general requirements

9. Requirements

During the design analysis phase and the rest of the design process a list is kept up with all the requirements for the product, which are shown here. The final product will be compared to this document.

Phase	Requirement type		Value
Production	Production techniques	Supporting structure Ballast covers	Water jet cutting, bending, extrusion, welding Compression moulding
	Materials	Mirror Supporting structure Ballast covers	Same thermal expansion coefficient Aluminum PVC
	Series size	Production number	500 - 10000
	Make or buy	Make Buy	Supporting structure, ballast Power inverter, motor, reduction gear
	Costs	Minimum field size	< € 2000 / m
Logistical	Dimensions	Aperture distance Length	1 m < 2.20 m
	Storage	Parabolic troughs	Piling up of sub-assemblies possible
	Assembly	Module assembly	As mouch as possible before transport to installation sight
	Transportation	ISO Containers	Module maximum wide -> see dimensions Piling up of sub-assemblies possible
Installation	Mounting	Easy to install Coupling Placement on surface	Plug-and-play Only one supporting part between two modules Coupling directly from receiver to receiver No permanent attachment to the surface >0.15m between surface and mirror Pitch between 2.25-2.75 m
	Weight	Module	< 350 kg for outer field module < 250 kg for inner field module < 100 kg / m^2
Use	Visual	Visually more attractive Distinctive design Ballast	Less mechanical look Differ in form from competitors Integrate form with supporting structure
	Reliability	Protection Corrosion Motor Rigid Thermal resistance	Glass plate protection optional Corrosion proof for more than 20 years Minimize torque as a result of structural weight Can withstand winds gusts of 100 km/h in protectional mode Materials with great thermal shock resistance in the concentrated area
	Maintenance	Mirror cleaning Inspection	With demineralized water (in case no glass plate protection is used) Component protection cover separable
	Tracking	Tracking accuracy Range	+/- 0.5 degrees > 150 degrees
	Profitable	Energy production LCOE	10% of total building energy supply Min. 10 kW system possible (after coupling) +/- $ 0.10 kWh
	Other	Shadowing Rain	Drive-shaft placed in shadowed part of the mirror Rain drainage from mirror without extra rotation of mirror
	Bonus		Indication about how well the system is performing
End-of-life	Demolition	Material	Possible to separate all different types of material Coding on different components for material type

Figure 18 Requirements

10. Functions of the single axis tracker

The functions of a CPVT system as a whole are already shown in Figure 7. For the development of the concepts, only the functions of the parts of the CPVT system that has to be designed must be clear. The single axis tracker itself, apart from the total system, only exists of the supporting structure, parabolic mirror, tracking system and receiver. The last one will be designed in detail by ENEA, so only basic properties of the receiver known so far will be taking into account. Of course the single axis tracker will have to be connected to the rest of the system in the end, so this must be kept in mind. The functions of the single axis tracker are then as follows:

- Produce electrical and thermal energy (as a covering function)
- Increase share of renewable energies in energy consumption
- Reflect and concentrate solar radiation
- Track the sun during the day
- Mount system on surface without permanent connection
- Support the parabolic mirror and receiver
- Couple different modules
- Protect system in case of extreme weather conditions

11. Wind loads

11.1 Introduction

The function of the structure to be placed on the surface without permanent connection, has a very strong influence on the design. The forces acting on the structure are in this case for the major part related to wind loads, depending on wind speeds. To withstand these loads, extra ballast is needed, spread onto the surface of the roof to distribute the pressure. The dimensions of the ballast component have a lot of influence on the load per square meter, because of the distribution on the one hand and the location of the rotation point of the structure on the other hand. The calculations in the next section will give the minimum dimensions of the ballast. As it is an iterative process, the dimensions given here are the final dimensions for one module. After the design and components were known, this detailed ballast dimensions could be given. Similar calculations where also done in the concept phase for first estimations.

The wind speed is directly related to the wind load. The wind speed almost never has a constant value in time but can be described by a mean value over a certain period between ten minutes and one hour; the mean value. A short period of 2-3 seconds increase in the wind speed is called a wind gust. These will produce peak loads on the structure, which define the design. Besides the wind gusts, the wind speed also depends on the height from the ground, the surface roughness (e.g. open field versus large city) and the place in a field of arrays of parabolic troughs. A parabolic trough at an edge of a field on a rooftop of a building in a large city for example has to cope with strong wind gusts.

From ENEA the mean value to design for is known for a typical Mediterranean city near a coast, namely 40 km/h. The nominal extra allowed ballast for flat roofs is also known for an average current domestic building with a value of 100 kg/m^2 (the maximum value lies around 200 kg/m^2). For the maximum building height 20 meters is chosen because the majority of the buildings in cities don’t exceed 7 stories, which is about 20 meters. The structure must be heavy to withstand strong winds, but at the same time it must be light to be able to stand on a flat roof of a typical house. A paper from Peterka (1992) describes the wind load design with the assumption of a ‘quasi-steady’ flow in which the wind gusts a derived from the mean wind speed. A more recent paper by Hosoya and Peterka (2008) however takes into account measured peak coefficients without deriving it from a mean wind speed. It is shown that with the earlier assumption the loads are underestimated considerably. The more recent paper is thus being used to calculate the forces on one parabolic trough module for the design of this project. After, these loads are compared to Italian and Dutch wind design load standards from papers of Cancro (2010) and Geurts and van Bentum (2003) respectively. The paper from ENEA written by Cancro gives the highest horizontal pressure on a parabolic trough, however it misses relationship between different positions of a trough under different wind directions like the paper from Hosoya and Peterka. A combination from Hosoya and Peterka and Cancro is therefore used to take into account the strictest regulations.

11.2 Calculation method Hosoya and Peterka

For a good understanding of the situation some drawings with the forces and dimensions are given in Figure 19 and Figure 20. After that the equations are summarized to calculate the different forces followed by an explanation of each unit on the next page. The units used in the paper are from the United States customary system and are converted to SI-standards in the end.

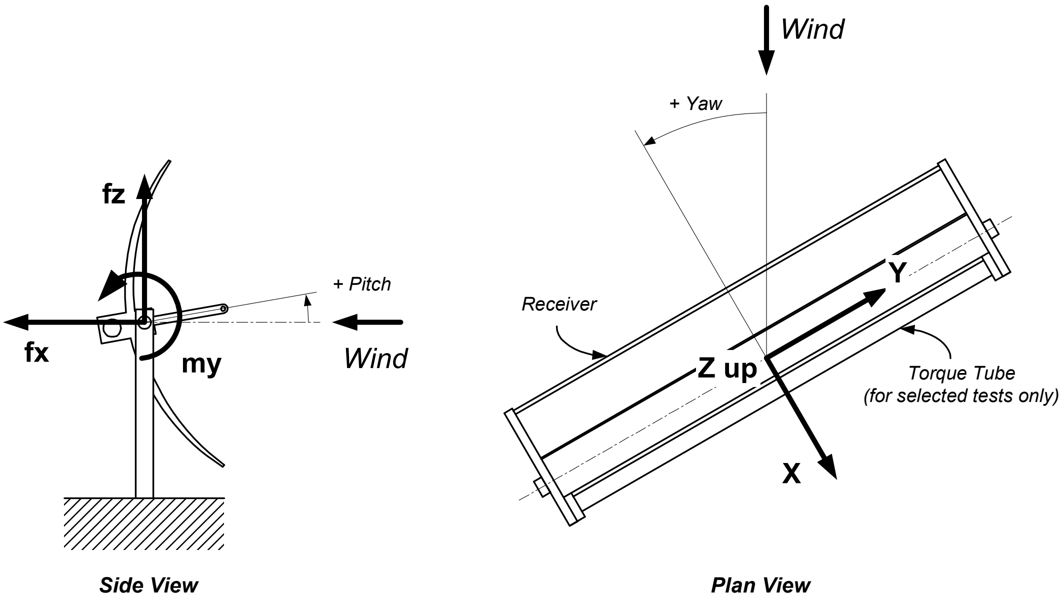


Figure 19 Definition of coordinate system (Hosoya and Peterka, 2008)

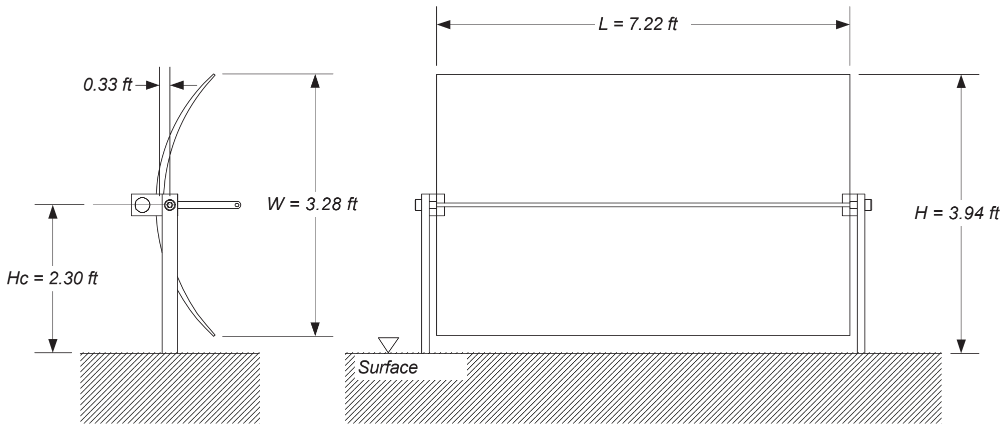


Figure 20 Key dimensions (drawing derived from Hosoya and Peterka, 2008)

Horizontal Force, $fx = qLWC_{fx}$ (3)

Vertical Force, $fz = qLWC_{f}$ (4)

Pitching Moment, $my = qLW\ 2C_{my}$ (5)

Dynamic pressure, $q = 0.00256 \cdot U^{2}_{h=20}$ (6)

Mean wind speed, $U_{h=20} = U_{h=5}\left(\frac{h_{20}}{h_5}\right)^{n}$ (7)

fx, fz, my = aerodynamic loads
C_{fx}, C_{fz}, C_{my} = aerodynamic load coefficients
L = spanwise length
W = aperture width
q = mean reference dynamic pressure
U = mean wind speed at the pivot height
h = pivot height
n = power law exponent, a measure of ground roughness

When the loads are known the base width can be calculated with the maximum ballast value of 100 kg/m^2 with the following formulas. For the use of these last two formulas the switch to SI-standards has to be made. To be able to place different modules close to each other, the base length is as long as the parabolic mirror itself.

$$x_{\min} = fx \cdot Hc + my = (P - fz) \cdot \left(\tfrac{1}{2} \cdot x_{\min}\right) \quad (8)$$

$$P = F_Z \cdot W \cdot L \cdot x_{\min} \quad (9)$$

$x_{\min}$ = mimum base width
Hc = shaft height above surface
P = base load
F_Z = gravity force
R = maximum roof ballast

The used values are summarized here for this particular case. With a shaft height above the ground of 0.20m there is still a minimum 0.20m of clearance between the parabolic mirror and the surface. The coefficients become clear from Figure 21.

$n = 0.35$ (center of large town, cities)
$U_5 = 40km/h = 24.86mph$
$L = 2.20m = 7.22ft$
$W = 1.00m = 3.28ft$
$h_{20} = 20m$
$h_5 = 5m$
$Cfx = 5.097$
$Cfz = -0.034$
$Cmy = 0.000$
$Yaw = 30^\circ$
$Pitch = 0^\circ$
$Hc = 0.70m$
$F_Z = 9.81m/s$
$R = 100kg/m^2$

Operational Mode (positove pitch angles)*

Case	Condition	Conf.	Yaw	Pitch	Cfx	Cfz	Cmy
1	Max Cfx	B3	30	0	5.097	-0.034	---
2	Min Cfx	B4	0	0	-1.242	-0.125	---
3	Max Cfz	B3	30	135	2.527	1.849	---
4	Min Cfz	B3	0	60	2.107	-5.256	---
5	Max Cmy	---	---	---	---	---	---
6	Min Cmy	---	---	---	---	---	---

Figure 21 Values of coefficients under heaviest loaded position of parabolic trough (Hosoya and Peterka, 2008)

By applying all values into the formula a minimum base width of 1.20m is found. A noticeable fact is that the maximum total moment around the axis, which eventually determines the minimum weight of the structure, occurs at a yaw of 30° instead of an expected 0° value. This has is due to aerodynamic reasons. The position of the parabolic trough that has to cope with the largest wind load is positioned at the outer edge of the parabolic trough field at the corner. With the relations between the coefficients from an outer edge module versus an inner field module, also this minimum base width can be calculated. Only the three 'C'-coefficients change, which leads to a minimum base width for an inner field module of 83.6% of the base width of an outer edge module. This value is used in the next section.

11.3 Calculation method Cancro

Where Hosoya and Peterka are taking into account horizontal and vertical forces, as well as moments around the rotation axis, the method of Cancro only deals with a horizontal force, which results in a larger minimal base width for the outer edge position of the parabolic trough, as can been seen next. This is largely due to the larger velocity of the wind speed to satisfy Italian regulations. The same figures can be used as Hosoya and Peterka as to see where the load acts on the trough.

$$fx = N \cdot A = q_b C_e C_p C_d \cdot A \qquad (10)$$

$$q_b = \tfrac{1}{2} \rho \cdot v_b^2 \qquad (11)$$

$$C_e(z) = k^2 C_t \ln\left(\frac{z}{z_0}\right)\left[7 + C_t \ln\left(\frac{z}{z_0}\right)\right] \qquad (12)$$

N = pressure on parabolic mirror
A = frontal area of structure
q_b = dynamic pressure
C_e = exposure coefficient depending on the placement height
C_p = form coefficient depending on form of the structure and direction with respect to the wind
C_d = dynamic coefficient depending on vibrations of structure
ρ = density of air
v_b = reference speed
k = class of exposure (in this case a coastal position)
C_t = coefficient for the topographical location
z = height of placement
z_0 = reference height

The used values are summarized here.

$A = 2.2m^2$
$\rho = 1.25kg/m^2$
$v_b = 27m/s$ (design speed at 5m that ENEA Portici uses as reference)
$q_b = \tfrac{1}{2} \cdot 1.25 \cdot 27^2 \approx 456N/m^2$
$C_p = 1.2$
$C_d = 1$ (structure with neglectable vibrations)
$k = 0.19$
$C_t = 1.1$ (Portici)
$z = 20m$
$z_0 = 5m$

A horizontal force fx of 3893 N will in combination with Equation 8 lead to a minimum base width of 1.59 meters instead of the 1.20 meters derived from Hosoya and Peterka. This value will be used for the outer edge parabolic trough module in the field. For the rest of the field the base sizes could be smaller because of smaller wind loads. The difference between the coefficients from Hosoya and Peterka (83.6%) can be used for the determination of these dimensions and lead to a size of 1.33m. To keep the production costs lower and because the difference between the base widths is small, a universal width of 1.59m is finally used.

12. Concepts

With the functions the tracker must fulfill, the dimensions of the ballast and the requirements, three concepts are developed. Some aspects of the concepts don't fit the requirements perfectly but are added in the case the requirements in the future development are still subject to change. After the introduction of the concepts, parts of different concept are chosen for further development. During the concept phase, numerous of sketches and drawings are made. An impression is given in Figure 22, which also shows three morphological schemes.

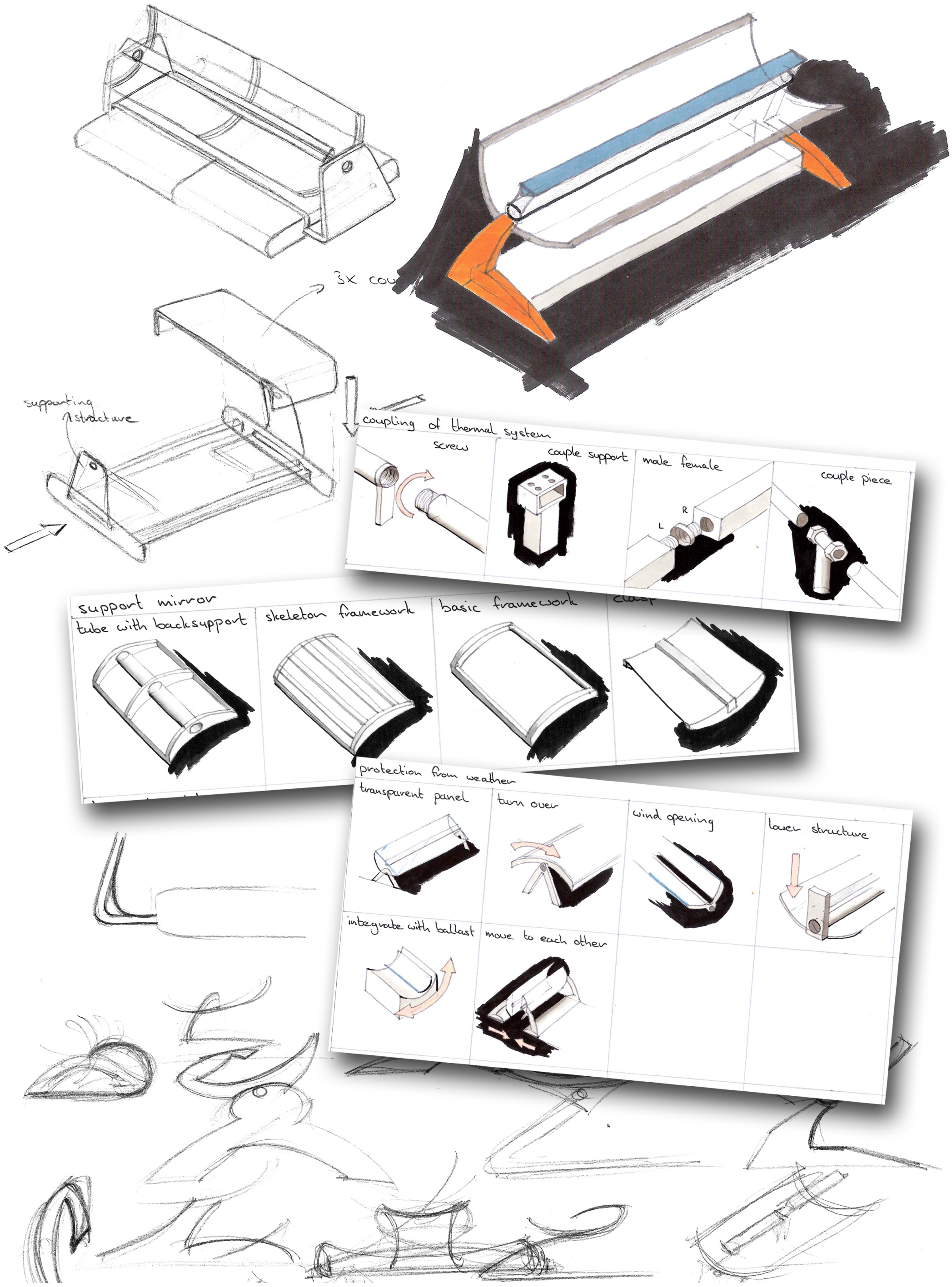
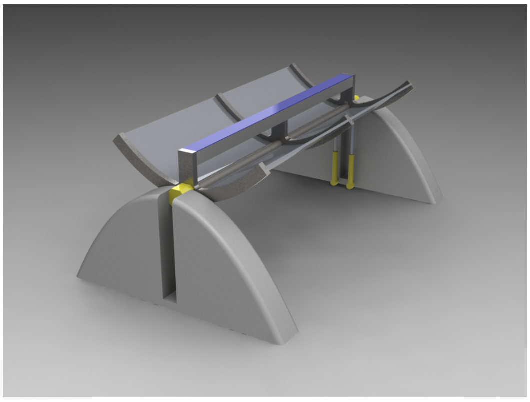


Figure 22 Sketches and drawings during the concept phase

12.1 Concept 1



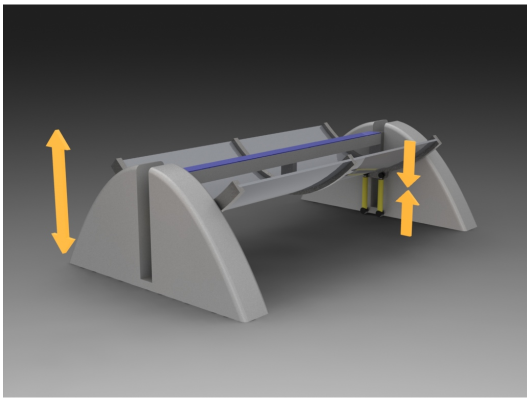


Figure 23 Concept 1

Figure 24 Protection against weather

The first concept is designed for modern or new buildings with relatively strong roofs. With the ballast on the side the weight is more concentrated compared to the other concepts, so it's unsuitable for older building with roofs that are less strong. The main advantage of these hollow ballast tanks is that they can be filled up with components like the power inverter and system control. Remained space can be filled up with sand to get the desired total weight.

By lowering the structure with a hydraulic system as shown with the orange arrows in Figure 24, the structure can be protected from heavy wind loads and power failures. It is a complex and expensive way of protection but in combination with rotation it could be an option for locations with extreme weather conditions for example.

Figure 25 Vegaflex mirror (Vegaflex, 2010)

For reflecting the solar radiation an integrated Vegaflex mirror with supporting structure is used from the Italian company Almeco (Almeco, 2010). By using four smaller panels, there is a small space between the drive shaft and the mirrors, for the drainage of rain with dirt (see Figure 25 and Figure 26).

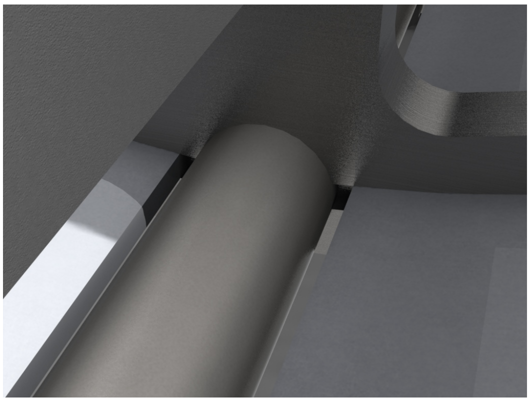


Figure 26 Rain drainage near drive shaft

The coupling of different modules is done through the drive shaft. Every module first transfers the water and electricity to the shaft so that the system can be coupled without having problems of collision between the ballast and receiver.

12.2 Concept 2

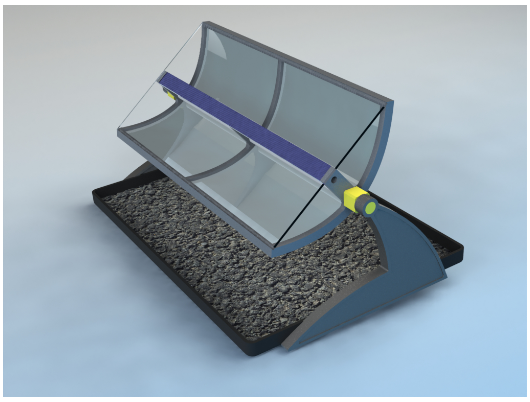


Figure 27 Concept 2

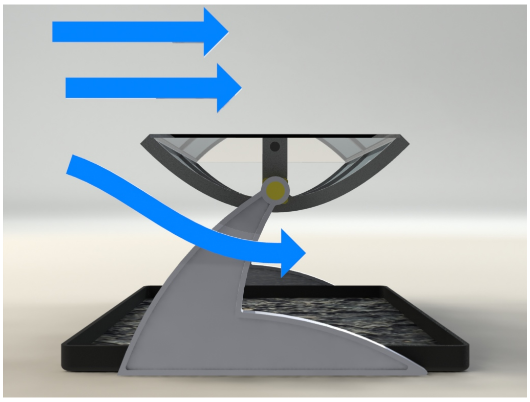


Figure 28 Wind protection

The second concept has its ballast distributed under the trough, therefore making it also suitable for roofs that have an average load capacity. The ballast is an open box filled with gravel, which makes it very easy to install on site. With a thin mirror taped on a substrate of honeycomb panels of aluminum and fiberglass, it has the advantage to use a technique ENEA already used for the Archimede project.

A glass plate protects the mirror from damaging but also has a few other advantages. The wind loads can more easily flow over the parabola (Figure 28) and special rain drainage is not needed any more. The plane surface makes cleaning more easily. Though it requires extra work during installation and from a visual point of view it is not the most beautiful; this concept makes the total system effective and the cheapest solution of the three concepts developed.

Receivers of different modules are coupled by extending the receivers by coupling them directly. Point of attention hereby is the tracking range of the system. To minimize the torque on the electromotor used for tracking, the drive shaft is placed just above the mirror near to the centre of weight of the parabola (Figure 29).

Although the installation of the ballast is simple, system components cannot be integrated very well in the module. This requires more adjustments of the building. Also big parts like the ballast tub and the glass plate are not easy to use during installation.

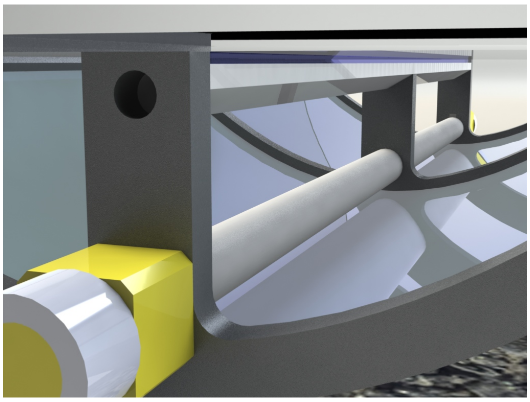


Figure 29 Minimizing torque on drive shaft

12.3 Concept 3

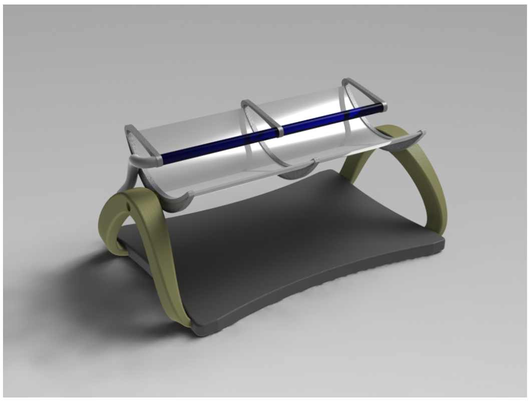


Figure 30 Concept 3

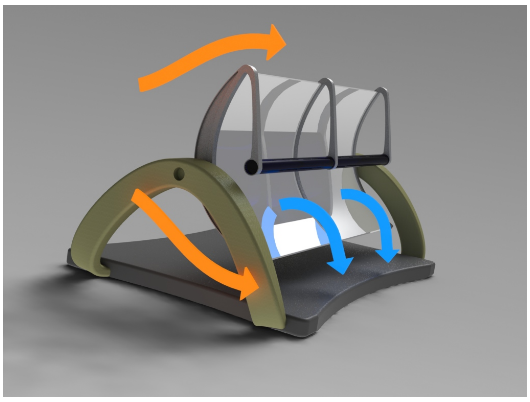


Figure 31 Rain drainage and wind protection

Vegaflex mirrors are also used on the last concept, in this case with only two parts instead of four. For simplicity during assembly this is preferable, only in case it's raining another solution is needed in the form of rotation of the trough. When the system turns, the rain is able to slide off the mirror. Protection from strong wind gusts is also done by rotating the rear side of the mirrors into the wind as shown in Figure 31. Due to the supporting structure it is not possible to rotate completely which is a disadvantage in the case of varying wind directions.

Because of the aesthetical point of view this concept has the drive shaft placed under the mirror. This commands high performance of the electromotor used for the tracking because of the high torques that are developed this way, due to the location of the centre of gravity from the trough with respect to the shaft. The abstract design of the different parts makes them easy to distinguish and is therefore an advantage during installation, but a disadvantage looking at production costs. Compared to competitors it's possible this design opens up new markets.

The ballast is made from an open box, which can be first filled by components such as a needed power inverter. The left over space can be filled with sand for extra ballast and the box is then closed with a cover. To make the design of the ballast fit the rest of the structure, production costs tend to be more expensive compared to the first concept.

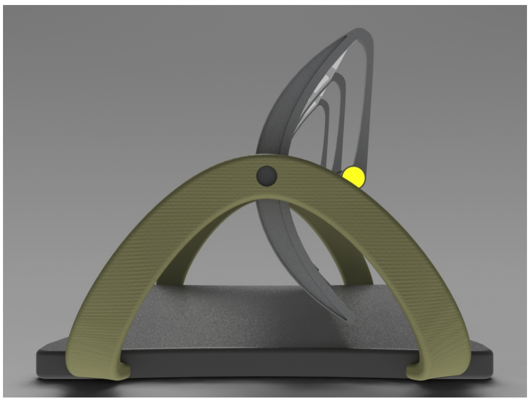


Figure 32 Collision of receiver and support at a 90° angle

To get a high efficiency of the thermal flow, the different modules are coupled by connecting the receivers in a straight line. This can lead to a problem with the range of tracking. The supporting structure will collide with the receiver when it's upright (Figure 32). It depends on the size of the receiver which forms are possible for the support to come up with the requirements for the range.

13. Concept choice

As mentioned before it depends on the field of application and other preferences which parts of the concepts can be best combined for further development. The choices from ENEA keeping the requirements in mind are presented here, followed by an overview of the pros and cons of the different concepts on the next page that highlights the parts that will be combined for the final product.

Until today the first priorities of solar concentrating systems is to make them as efficient and cost effective as possible. Of course this remains very important in the development of the product but a trend of giving the products nice aesthetics is not yet common for concentrating solar systems. For PV modules nowadays, there are more options available regarding this area. ENEA wants to distinguish itself from competitors by also taking into account aesthetics as an important factor thereby making costs not the driving factor. Concept 3 fits these requirements the best of all three and is therefore the basis for further development.

Looking at the other aspects, the solutions of concept 3 are not in every case the best option. To minimize the torque load on the motor the drive shaft must be placed as close as possible to the center of weight of the parabola. This point is located between the receiver and mirror and therefore the axle will be placed above the mirror. From an aesthetical point of view it doesn't make any difference because sometimes the front- and sometimes the rear-side of the mirror will be seen. To get rid of rain it is best not having to turn the system around every time it gets wet. Therefore the mirrors split in half from concept 1 are the best option. The opening can be nicely put away behind the drive shaft and won't affect the efficiency while it's placed in the shadow of the receiver and drive shaft.

Because full rotation is not needed for protection from the wind, the structure can have a symmetrical shape, reducing loads. With a closed ballast under the structure, the ballast space is suitable for placing some of the system components while distributing the load per square meter. A system can then be applied on any flat roof with enough space and average strength, making it suitable for existing cities like Madrid and Naples. The option of placing some components in the ballast helps to minimize the adjustments needed on a building. Furthermore a glass protection must be integrated as an option protecting the expensive mirrors even more, giving potential customers more opportunities for their specific whishes.

Some downsides of the concept thus need to be overcome. These downsides lead to the following points of attention for which concept 3 needs to be changed.

- Split up mirrors making them suitable for rain drainage
- Drive shaft placement above mirror tot minimize torque loads
- Redesign of support structure to match the tracking range specifications
- Addition of an optional glass protection
- Avoid big parts to reduce production costs and make installation more easy
- Integrate design of support structure and ballast so it forms a harmonious entirety
- Take into account the possibility of adjustable ballast wide for in-field modules (which is finally skipped, see chapter 11.3 Calculation method Cancro)
- Support structure must be able to support a module on both sides so that only one support is needed between two modules

ENEA's opinion	Concept 1	Concept 2	Concept 3	Part
• possible to try a new sort of mirror type • when cost effective buy finished products	4 parts slide-in Vegaflex + rain drainage + assembly	2 parts glue on substrate + experience by ENEA - assembly - rain drainage	2 parts slide-in Vegaflex + assembly	mirror
• lowest torque on electromotor	between mirrors + integration with rain drainage	above mirrors + torque load motor	under mirrors + cleaning mirrors - torque load motor	axle
• glass protection must be an option • full rotation is maybe not needed	lowering structure + self protecting Vegaflex - costs - complexity	glass substrate + cleaning + rain drainage + wind loads - costs - visual	rotation + self protecting Vegaflex + simple structure - design freedom supports - varying wind directions	protection
• field of application are first the current buildings	both sides + integration of parts + design + side wind protection - load on surface	under structure, open + ease of installation + costs + flexibility - aesthetics	under structure, closed + design - production costs	ballast
• distinguish in design from competitors • design is more important than costs	parabolic + a whole with trough - looks heavy from the side	asymmetric + opportunity for rotation - loads on structure	abstract + distinctive design + architectural possibilities - production costs	design
• efficient thermal flow • avoid unnecessary complexity of the system	trough axle + design freedom ballast - system complexity - efficiency thermal flow - costs	prolongation of receiver + simple structure	prolongation of receiver + simple structure - maximum rotation angle	coupling
• as much pre assembly as possible	partly on location + small parts + integration of components in ballast - complexity of lowering structure	partly on location + filling up ballast - rigidity of glass protection - big parts	partly on location + distinctive parts + integration of components in ballast - big parts	installation
• enough accuracy without too much costs	drive: electromotor tracking: sensor + GPS + availability of components + accuracy - costs	drive: electromotor tracking: sensor + availability of components + cost - accuracy	drive: electromotor tracking: GPS + availability of components + accuracy + aesthetics	tracking
• minimal adjustments of building	integrated in ballast + aesthetics of field + use as ballast - maintenance	outside modules + maintenance - aesthetics of field - adjustments building	partly integrated in ballast + aesthetics of field + use as ballast	power inverter system control

not a good option
possible option
good option
good option, chosen one

Figure 33 Concepts overview

14. Final Design

Before focusing on all the details of the final design a short description is given here. A render with the major dimensions of one module is given in Figure 34. One motor under the parabolic trough in the backside module drives both modules. This combined system is called a unit. The current bottleneck in the minimum field size however is the power inverter, for which four units is the minimum to get an efficient energy production. Each module consists of a ballast part from PVC material which can be filled with sand to get the required weight to withstand wind loads. This way no adjustment on the existing roof of the applied building is needed. The ballast part can be made in almost every color to aesthetically fit the building it will be applied to. The parabolic trough is supported by an aluminum supporting structure to save weight and harmoniously integrates the ballast with the trough. The trough consists of a mirror made from an aluminum sandwich structure in a certain radius, covered by an optional glass plate. To protect the system from heavy weather conditions the system turns it's parabola until it's aimed straight up, so that the surface exposed to the wind is minimized. The glass plate protects the mirror from weather conditions like hail for example and makes it easier to clean the system. Without glass plate an extra layer can be made on the mirror to protect the mirror surface but is less rigid than the straight glass plate. The glass is made from clear glass with high transmittance not to affect the total efficiency too much. One module including a glass plate and motor weighs around 250 kg without sand. For Naples in Italy, for which this system is designed for, this can be increased to 350 kg which is needed for outer edge modules to withstand the wind loads in this city. For other locations more or less filling up of the ballast may be needed and also the thickness of structural components can be changed. There is a certain amount of margin left in the design for these adjustments if necessary.

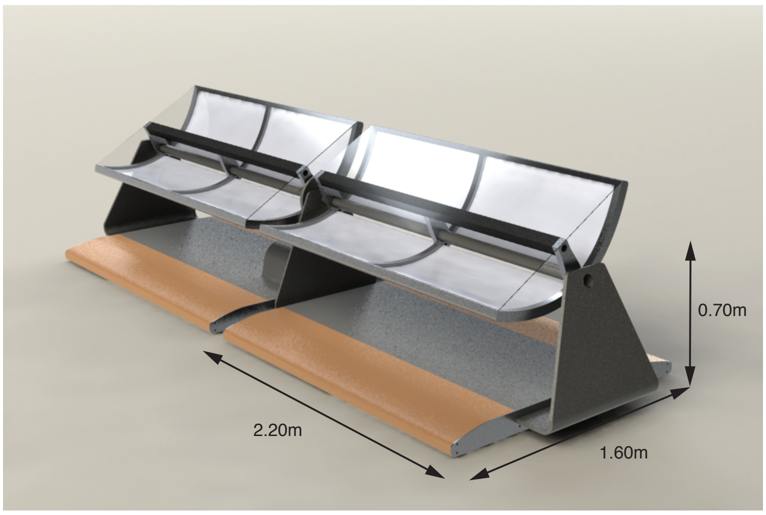


Figure 34 Final design of two modules with dimensions

The supporting structure on the sides can be replaced by the same supporting part as is used in the middle to connect more modules in a long row. This makes the system modular because also the receiver can be connected by a coupling part. In this stage of the design process however the receiver remains a black box because it is still being developed. An estimation can be made for the electrical part but for the thermal properties more information must be known. When a field of modules is placed on a roof the thermal piping from the receiver and electrical cabling can enter the building at the location nearest to meter cupboard and plumbing installation. In the building the warm water storage, pumps, power inverter and system control can be placed. The only things placed outside are the modules, the thermal piping and electrical cabling. In the following sections of this chapter all aspects of the single axis solar tracker will be discussed in detail.

14.1 Optimum Pitch

The pitch between different rows of parabolic troughs is the distance between the rotating axes of two modules that are placed in front of each other. When the sun sets or rises the outer edge row of parabolic trough can shadow the other rows. However, the more troughs are placed on a certain area, the more sun you will be able to catch. Their percentage of losses due to shadowing will however be higher and will make each trough less efficient and relatively more expensive regarding the LCOE.

To make an estimation for the optimum pitch of a regular site, a software package from the University of Geneva is used (PVsyst, 2010). It is capable of modeling a site with flat PV panels the size of the parabolic troughs to approach the size of these systems. An example of a rooftop at 12 meters of height with seven rows of parabolic troughs can be seen in Figure 35.

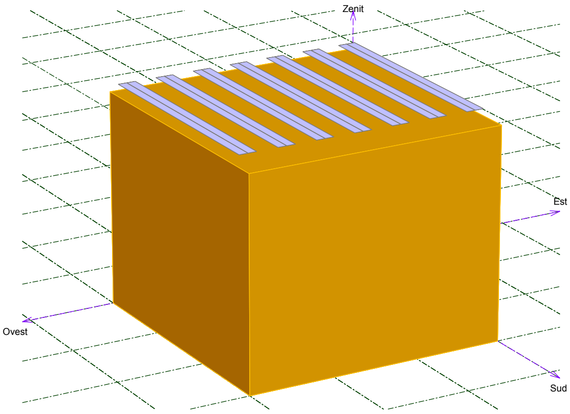


Figure 35 Model of a rooftop with rows of solar concentrators (PVsyst, 2010)

Naples is chosen as the example location with a north south orientation of the drive shafts to reach the highest efficiency possible. In the final report of the program (Figure 36) the losses because of shadowing can be seen as a percentage of the total yearly energy production for a chosen pitch. For a pitch of 2.5 m the annual loses caused by shadowing are 8.2%.

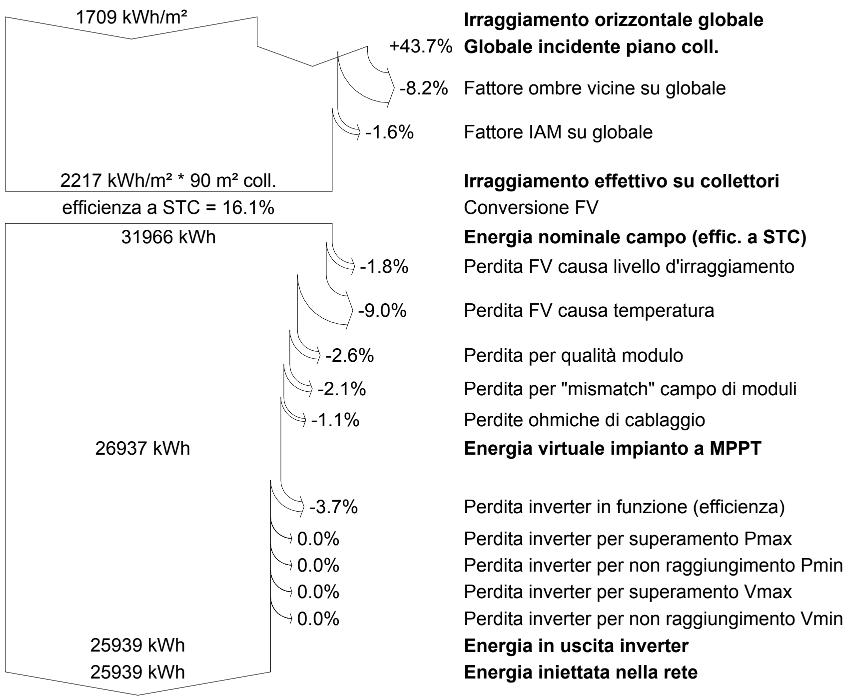


Figure 36 Loses in percentages of total caught solar radiation for a pitch of 2.5m (‘Fattore ombre vicine su globale’ is the shadowing factor, is this case 8.2%) (PVsyst, 2010)

By running the program several times for different pitches the following graph originates. The 'knee' of the graph is the most interesting part. Here, the losses are not too large but also the pitch doesn't increase to fast. Red lines mark this knee of the graph. For the general case, a pitch of 2.5 m is a good compromise. For each application however the pitch can be different. Total annual production, cost of ground, costs of solar concentrators, location and logistics all have influence of the choice of the final pitch. For the case of a certain area of rooftop for example, a total power of 10 kW is needed but the area is limited; the pitch can be smaller than 2.5 m. For a farmer on the other hand where the area is no bottleneck, the pitch can be as large as say 5.0 m, to have a larger efficiency of the solar concentrators. Also for maintenance reasons a minimal pitch of more than 2 m is desirable. With the ballast of two rows filling already 1.6 m of space, some extra space between different rows allows some space for installing, maintenance and cleaning of the modules.

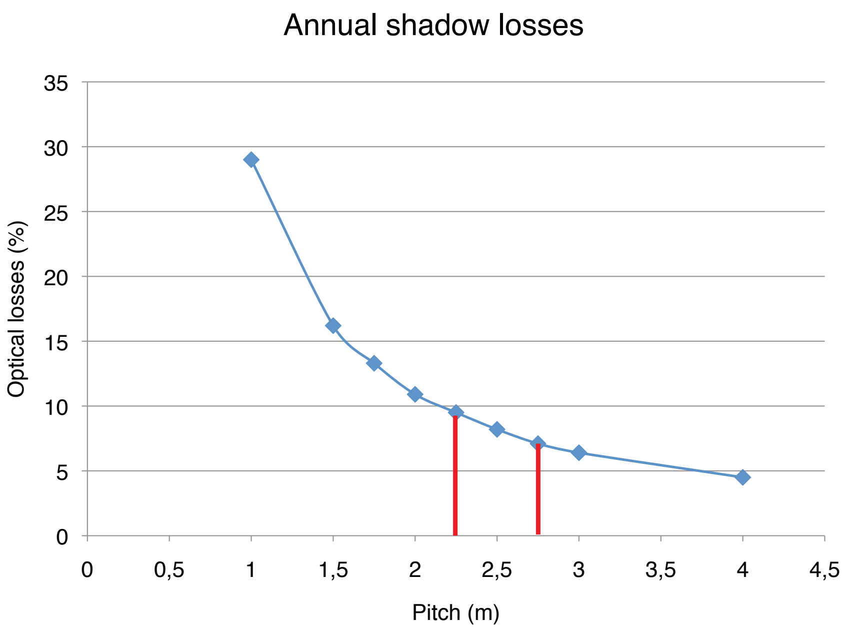


Figure 37 Losses for different dimensions of the pitch

14.2 Motor

Tracking the sun requires a motor in combination with a reduction gear and cogwheels to drive the shaft really slowly during the day. Because a certain torque can only be obtained with a relatively high rpm of the motor, a reduction gear and cogwheels are needed to drive the shaft slowly. The choice for the electromotor depends on the torque and maximum speed of rotation. The torque can be derived from the digital 3D model and gives 310 Nm per module including the optional glass plate. For protection against strong wind speeds to parabola has to change direction much faster than under normal operation conditions. Because the protection mode is a horizontal position a maximum distance of about 90° is the maximum angle the parabola has to rotate in a chosen time-span of 15 seconds. This represents an angular velocity of about 0.1 rad/s (1 rpm). The needed power for the motor can be calculated with equation 13.

$$P_{motor} = \frac{N \cdot T \cdot \omega}{\eta_{rg} \cdot \eta_{ts}} \qquad (13)$$

N = number of modules

T = maximum torque per module

ω = angular velocity

η_{rg} = efficiency reduction gear

η_{ts} = efficiency transfer system (cogwheels and chain)

Figure 38 Omron Accurax G5 10030H (Omron, 2010)

The number of modules per driving system is two. This is done for aesthetical reasons so that these parts can be placed in the middle of these modules to be less noticeable. More modules is possible looking at available electro motors but this makes the system less flexible. With the given values and an average efficiency of the reduction gear and transferring system of 80% and 95% respectively the needed motor power is 85W. A manufacturer used by ENEA for these kinds of systems is Omron. From this manufacturer a motor with a relatively low number of revolutions is chosen with enough power to drive the two modules into the protection mode. The most appropriate motor is the Omron Accurax G5 10030H shown in Figure 38. It is a small 100W motor with a nominal angular velocity of 3000 rpm and works on 230V. For an exact datasheet see appendix A.

14.3 Reduction gear

A reduction ratio from a gear is the most important value describing the ratio between the angular velocities of the input versus the output. Very high reduction ratio's are available but are expensive and lack a high accuracy which is needed in this application. Therefore a combination with cogwheels has better performance. From the experience of ENEA the manufacturer Bonfiglioli from Italy is used for the selection of the reduction gear. The power range of the motor and reduction ratio determine the type of reduction gear. With a cogwheel ratio of 1:3 a reduction ratio of 1:1000 from the reduction gear is possible to transfer from 3000 rpm from the motor to a maximum of 1 rpm for the parabolic trough. For normal operation speeds the motor angular velocity is lower than this which can be adjusted by the system control.

Normal and maximum torque values of the motor and reduction gear are compared as not to exceed the forces the reduction gear can handle. The Bonfiglioli Planetary Drive 304 L4 1018 (Figure 39) remains as the most suitable gear for this application. With a reduction ratio of 1:1018 it fits the requirement almost perfectly. The dimensions allow the reduction gear to be placed under the parabolic trough but it doesn't totally fit in the ballast part so an additional cover panel is needed. For an exact datasheet see appendix B.

Figure 39 Bonfiglioli 304 L4 1018 with electromotor (Bonfiglioli, 2010)

14.4 Receiver

The heart of the solar concentrator is the receiver where the radiation from the sun is converted into electricity and warm water. Investigation is still done on this part and thus the specifications are not yet known. It is an advanced component which requires specialists to design it and therefore the design of the receiver is beyond the scope of this assignment. However for the estimation of the performance of the total product and the choice of the power inverter for example some aspects have to be known. An estimation for the electrical part can fairly easy be done, for the thermal part this is much more difficult and is in this stage of the product design not yet possible.

For choice of PV cells the concentration ratio is chosen as 20 which is a little conservative for solar concentration applications. This is the ratio between to total flat mirror area and the PV cell area. With an aperture diameter of the parabola of 1 meter this results in square PV cells of 5 x 5 cm. Average performance values are taken for the PV concentrator cell that are given in Table 2. Because one unit exists of two modules with a total of 4 meters of receiver, also the values per unit are given in this table in which 40 PV cells are connected in series. With these values it is possible to find a suitable power inverter.

	PV cell	Unit (2 modules)
efficiency η	18%	18%
area A	0.025 m^2	0.1 m^2
peak power P_P	9 Wp	720 Wp
open circuit voltage V_{OC}	0.7 V	56 V
max. power voltage V_{MP}	0.6 V	48 V
max. power current I_{MP}	15 A	15 A
short circuit current I_{SC}	17 A	17 A

Table 2 Estimated electrical characteristics of receiver

14.5 Power inverter

The direct current has to be converted to alternating current which is the task of the power inverter. Looking at the specifications from Table 2 a power inverter can be chosen. The smaller commercially available power inverter have a minimum needed voltage of 150 V compared to the 48 V of maximum power voltage for one unit. Therefore the power inverter is the limiting factor in the minimum field size of total system. Four units are needed to connect to the Fronius IG 30 power inverter shown in Figure 40 that has specifications closest to what is needed. The dimensions of this component doesn't allow it to be placed under the trough in the ballast so it must be placed in the building like the water storage and system control. For an exact datasheet of the Fronius IG 30 see appendix C.

Figure 40 Fronius IG 30 (Fronius, 2010)

	4 Units (8 modules)		Fronius IG 30
peak power P_P	2880 W	PV system output	2500 – 3600 W
open circuit voltage V_{OC}	224 V	max. input voltage	500 V
max. power voltage V_{MP}	192 V	max. power point voltage range	150 - 400 V
max. power current I_{MP}	15 A	max. input current	19 A
short circuit current I_{SC}	17 A	Euro efficiency	92.7%

Table 3 Specifications power inverter compared to minimum field size

14.6 Mirrors

The most important aspect of the mirror surface is a high reflectance of solar radiation to get more energy onto the receiver. Different kind of techniques are used in which a thin layer of aluminum or silver accounts for the reflection. This layer can be coated onto a glass or metal sheet but also layers of polymers are used as a basis. The reflective layer is then protected by a glass substrate. Different kind of materials have different thermal expansion coefficients that affects the total accuracy. The Almeco Group has it's origin in Italy an makes the Vegaflex product; a mirror element consisting of an aluminum substrate with a thin aluminum reflective coating Figure 41. Because the product has it own strength from the aluminum substrate, the mirror can remain light. The Vegaflex can be ordered in the right curvature and is very form tight because all components have the same thermal expansion coefficient. A solar reflectance rate of 93% can be obtained with a weather resistant topcoat in the case no glass plate is added as an option. Without this coating the reflectance increases to 95%.

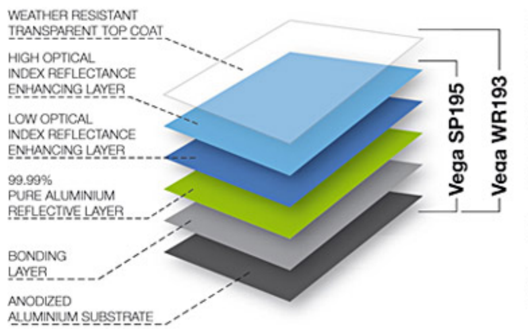


Figure 41 Vegaflex layers (Almeco, 2010)

14.7 Glass plate

A high solar energy transmittance makes normal float glass not applicable for the protection of the mirror and receiver from dust and extreme weather conditions. Therefore a special ultra clear glass is used, also called low iron glass. This sort of glass is produced by different manufacturers over the world and has a transmission rate of about 91% for a plate of 4 mm thickness (Cityglass, 2010). Because the weight of the plate lies relatively far from the drive shaft, more torque is needed from the electromotor. Per unit two glass plates of each 20 kg are needed for a thickness of 4 mm. The main advantage is the product life of the mirror parts and the ease of cleaning the parabolic troughs. From the experience of the Archimede project, hail contributes largely to the decreasing performance of mirrors. Despite the extra initial costs and performance drop of the glass cover, it can be a desirable option for customers looking at the total life cycle of the system.

14.8 Materials

The basic thought behind the solar tracker is to develop a product to gain sustainable energy. Also the production of the system is part of its lifecycle so sustainability is also a topic here. For the construction and supporting parts an analysis is made with the CES Edupack 2009 software between aluminum, stainless steel and carbon steel. Also plastics where considered in the first phase but they had not enough strength to support the construction. To explain the choice between these three metals, one side of the shaft support is taken as an example (Figure 42). With the stress and displacement analyses from appendix D is has become clear what the minimum thickness of this part must be to keep the deflection within proportions under maximum loads to reach the right accuracy. Also the maximum stress must have a lower value than the yield stress in this case. With aluminum as a starting point a comparison can be made between stainless steel and carbon steel. In these cases the part has a different thicknesses to get the same performance as in the aluminum case with regard to the displacement under maximum loads. An overview between the different materials and their total weight, price, strength and contribution to the pollution of the environment can be seen in Table 4. The item water usage shows how much water on average is needed to produce these materials. The embodied energy is the non-renewable energy consumed in the total lifecycle of a material, from acquisition of raw materials until their replacement and recycling. Included in the embodied energy are their processing, manufacturing, transportation to site, construction, maintenance, repair, restoring, refurbishment and replacement (Canadian Architect, 2010).

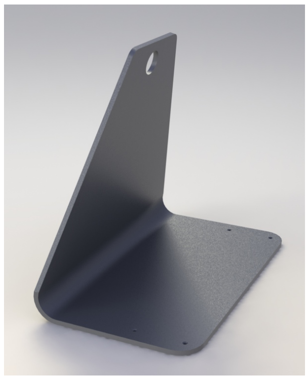


Figure 42 Shaft support side

	aluminum	stainless steel	carbon steel
material type	1050A-H9	AISI 304L	AISI 1050
needed thickness	15 mm	10.9 mm	10.7
density	2700 kg/m^3	8000 kg/m^3	7900 kg/m^4
needed material	32 kg	69 kg	67 kg
yield strength (minimal)	160 MPa	190 MPa	325 MPa
density	$2.7 \cdot 10^3$ kg/m^3	$8.0 \cdot 10^3$ kg/m^3	$7.9 \cdot 10^3$ kg/m^3
material costs*	€ 38.40	€ 228.70	€ 17.60
water usage*	32.000 L	15.180 L	3.350 L
embodied energy*	6.400 MJ	5.590 MJ	2140 MJ
CO_2 emission during primary production*	304 kg	352 kg	168 kg

** total amount per shaft support*

Table 4 Comparison between different metals

Although stainless steel has the better values looking at the material per kg, the part becomes so heavy to reach the desired performance that aluminum is a better choice. The stainless steel only uses less water during production, but is far more expensive and too heavy for the total structure when the allowable ballast on roofs is taking into account. The same can be said from the carbon steel but regarding all other aspects it’s superior to aluminum. However, despite the fact that also carbon steel for this part makes the structure to heavy, there are some other aspects that make steel not the best option for all structural parts of the concentrating system.

Because this type of aluminum doesn’t need a coating to prevent it against corrosion it can be applied untreated. With its formed oxidation layer the aluminum is able to withstand all weather conditions. This gives the part a cleaner look which is nicer from an aesthetical point of view, but it also lacks a paint layer which is not environmental friendly. For the shaft and beams between two shaft supporting parts however, aesthetics and weight have less influence and they are already protected from weather influences by the rest of the structure. Here carbon steel is the better option because it’s cheaper and contains less embodied energy compared to aluminum.

The other ballast parts have only the function of supporting the ballast and cover it up. Therefore strength is of less importance so another material can be more suitable. A lighter and cheaper material is found in the category of polymers. A new comparison is made with the CES Edupack 2009 software. With a price limit per kg that is the same as for the metals, the option of recycling and the selection of only opaque and translucent materials; six sorts of polymers remain applicable. In the following figure polyvinylchloride (PVC) is the cheapest option with one of the lowest CO_2 footprints.

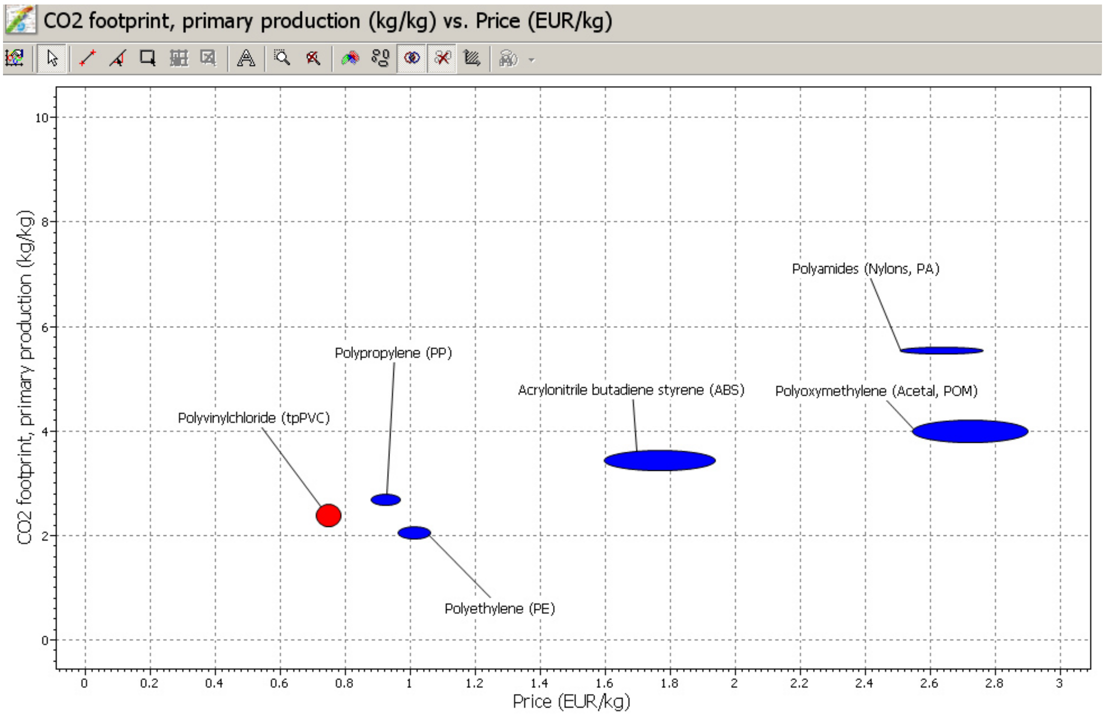
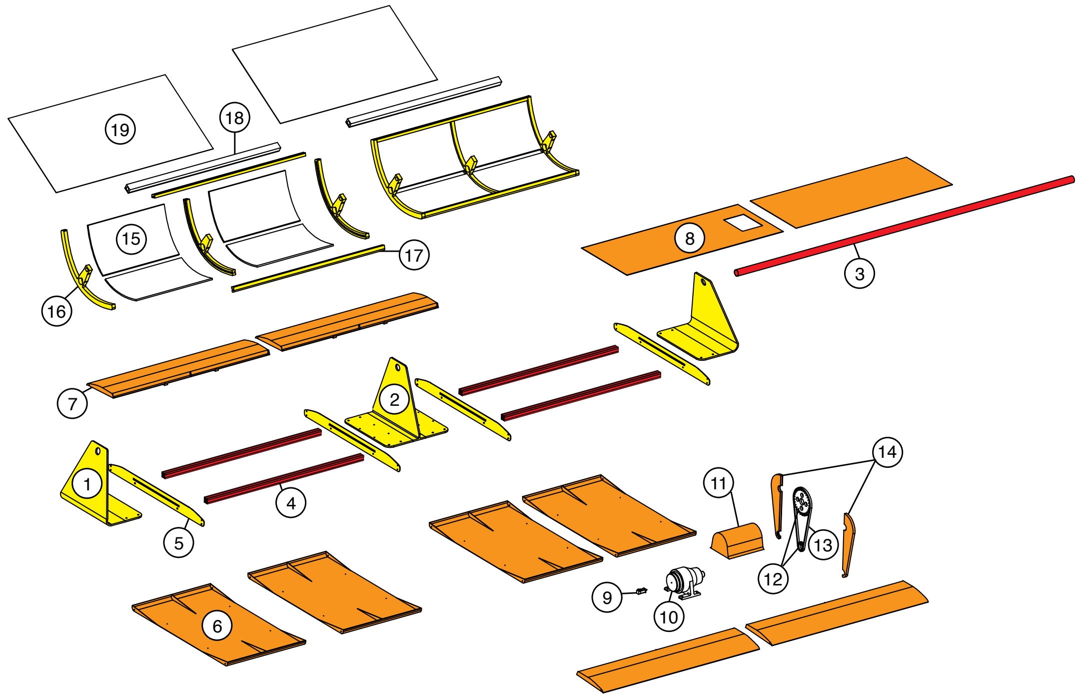


Figure 43 Price versus CO_2 footprint of different polymers

Other properties like yield strength, density and maximum service temperature are compared in figures that can be seen in appendix E, but have similar values. In this appendix, it can also be seen that PVC has the least embodied energy compared to the other plastics. Furthermore, PVC can easily be produced in different kind of colors and is suitable for compression molding to make relatively small series of products. PVC is therefore the best option for the production of the ballast cover parts. An overview of the materials of parts that cannot be purchased and thus have to be produced, is given in the exploded view in Figure 44 on the next page, that shows two modules that are connected with the middle shaft support.



1	shaft support side	8	ballast top	15	mirror		aluminum
2	shaft support middle	9	motor	16	mirror support		PVC
3	shaft	10	reduction gear	17	glass support		carbon steel
4	beam	11	reduction gear cover	18	receiver		
5	ballast side	12	cogwheels	19	glass plate		
6	ballast bottom	13	chain				
7	ballast cover	14	cogwheels cover				

Figure 44 Exploded view with materials

14.9 Assembly

Each module has a wide of somewhat less than 2.20m so it can fit in an ISO standardized container used on ships and trucks. The ballast part can therefore partly be assembled with bolts before transportation to the installation sight (see Figure 44). The same can be done for the parabolic trough with mirrors, mirror supports, receiver and glass plate. This allows a more easy installation on the building roof, where the modules then have to be connected and the installment of wiring and thermal piping can be done. The trough can be connected to the ballast via the shaft and cogwheels and the ballast can be filled up with sand as much as needed. Finally the cover and top can be placed over the ballast. Between al the PVC and the construction parts rubber strips prevent rain to reach the electrical components and the sand. Inside the building the water storage tank, pumps, system control and connection to the electricity grid and water supply have to be installed also. This order is applicable for smaller installation sites. For large fields it can be chosen to assemble al parts on the installation sight so that more parts fit in a truck. It depends on the field size, transportation costs and easy of placing pre-assembled parts on the roof how much there will be pre assembled. For a small sight where parts can be easily lifted towards to roof the following table gives an idea how the assembly can be done. For part numbers look at Figure 44. Sub assembly pictures are given below the table.

steps	parts	connection	result
pre-assembly phase			
1. attach	rubbers on all PVC parts	glue	sub-assembly 1
2. connect	6 to 4	bolts	
3. connect	5 to 4	bolts	
4. connect	1 to 4	bolts	
5. connect	9 to 10	bolts	sub-assembly 2
6. slide in	15 to 16	-	sub-assembly 3
7. connect	17 to 16	bolts	
8. connect	18 to 16	bolts	
9. attach	19 to 17	glue	
on sight			
10. connect	2x sub 1 with 2	bolts	
11. connect	sub 2 to 2	bolts	sub-assembly 4
12. slide on	12 on 3	slide	
13. connect	sub 4 to sub 3	part 3	sub-assembly 5
14. connect	wires and thermal piping		
15. fill	ballast with sand		
16. connect	7, 8, 11, 14 to sub 5	bolts	sub-assembly 6
in-building			
17. install	power inverter, water storage, water supply, connection electricity grid, pumps, heat dump radiator, system control		
18. connect	in-building components with modules		

Table 5 Assembly steps for a small field of application

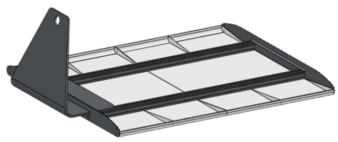


Figure 45 Sub-assembly 1

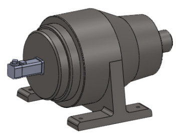


Figure 46 Sub-assembly 2

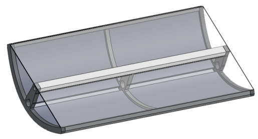


Figure 47 Sub-assembly 3

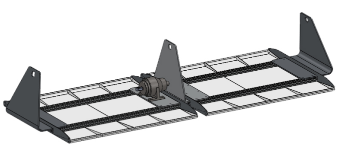


Figure 48 Sub-assembly 4

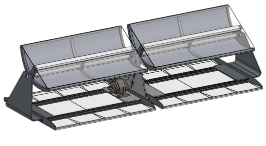


Figure 49 Sub-assembly 5

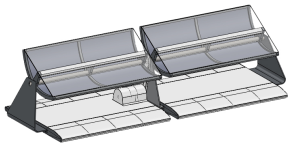


Figure 50 Sub-assembly 6

14.10 Production methods

The supporting structure made from aluminum parts and the PVC ballast part are produced using different kind of techniques. For the ballast side, shaft- and mirror supporting parts water jet cutting is used. This technique can be used for almost every material. For greater precision abrasive material can be used mixed with the water in the water jet. For the boltholes the same technique can be used. The supporting parts are then bent into the right angle through plate bending. The program BendWorks (CIRI, 2008) is used to calculate the minimum bending radius. For the middle shaft supporting part instead of plate bending, welding is needed because of the 'T' shaped form. Forces acting in the horizontal position on this part are much smaller than the bent supporting parts and 1050A-H9 aluminum has excellent weldability which makes this the right connection choice. The glass supporting parts can be made by extrusion because of its profile form which is constant along the length of the part.

For the ballast parts that are made of PVC the size of the parts and the production size make injection molding not suitable. Relatively large components have to be formed and the initial series size lies between 500 and 10000 as a first estimation. Compression molding however is suitable for PVC with lower tooling and equipment cost because of lower pressures. This makes it suitable for the estimated order of production series size. Examples of products made with these technique and material are LP's and canoes. In compression molding a pre-measured quantity of polymer in the form of granules or a pre-formed tablet is placed in a heated mold. The mold is closed creating sufficient pressure to force the polymer into the mold cavity. The polymer is allowed to cure, the mold is opened and the component removed. A mass range of 1-20 kg and range of section thickness of 1.5-25 mm is flexible enough for all the PVC parts needed (CES Edupack 2009).

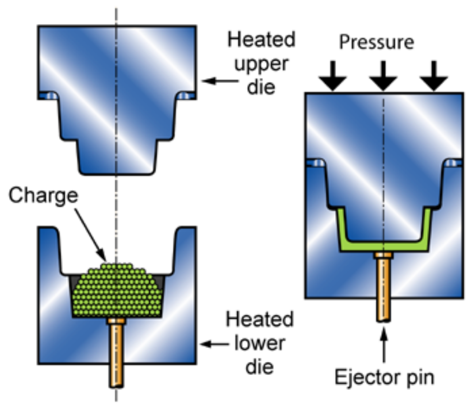


Figure 51 Projection molding process (CES Edupack 2009)

A disadvantage of molding the ballast parts is that 5 different molds are necessary from which three are large molds. The reduction gear cover can be integrated into the ballast top but this means it more difficult to pile up the sub-assemblies and leaves the other module in the unit with an empty space underneath this bulb.

14.11 Costs

With the experience ENEA has in the field of solar energy systems a first estimation of the costs of the system is made. The average costs of a competitor like Absolicon and comparable products like the Archimede CST system are taken as indicators with an average price of around 1200 euro's per meter of trough. With the cost breakdown of Figure 11 the costs of the different parts can be calculated. The cost breakdown percentages however have to be adjusted for the product of this project. In Table 6 the factors that are used can be seen that have been chosen in corporation with ENEA. The foundation has a zero factor because no permanent attachment to the surface is needed any more. Mirrors, drivers, thermal piping and other components like water storage and pumps for example will not differ that much from the current prices. Yet the structure and receiver will change considerably. The use of aluminum and the whole ballast part will make the structure more expensive than a carbon steel structure that is just functional. Also the receiver includes PV cells, which are not applied in the cost breakdown for a CST system of Figure 11. Furthermore because of the addition of the PV cells to make it a hybrid system more instrumentation is needed in the form of a power inverter and more electrical cabling. The factors are multiplied by the old prices and then a new cost breakdown is made which is shown in Figure 52. The structure is now an even more important factor resulting in a price of around € 1530 per stretching meter. A minimum field size of eight modules will therefore costs around € 25,000.

part	old %	old price	factor	new price	new %
foundation	8.7%	€ 104.40	0.0	€ 0.00	0.0%
mirrors	19.1%	€ 229.20	1.0	€ 229.20	15.0%
drivers	6.2%	€ 74.40	1.0	€ 74.40	4.9%
structure	22.5%	€ 270.00	2.0	€ 540.00	35.3%
receiver	20.6%	€ 247.20	1.5	€ 370.80	24.3%
instrumentation & control	6.7%	€ 80.40	1.2	€ 96.48	6.3%
connecting cables	4.8%	€ 57.60	1.4	€ 80.64	5.3%
thermal piping	3.3%	€ 39.60	1.0	€ 39.60	2.6%
others	8.1%	€ 97.20	1.0	€ 97.20	6.4%
total	100.0%	€ 1200.00	1.2736	€ 1528.32	100.0%

Table 6 Price estimation of different components

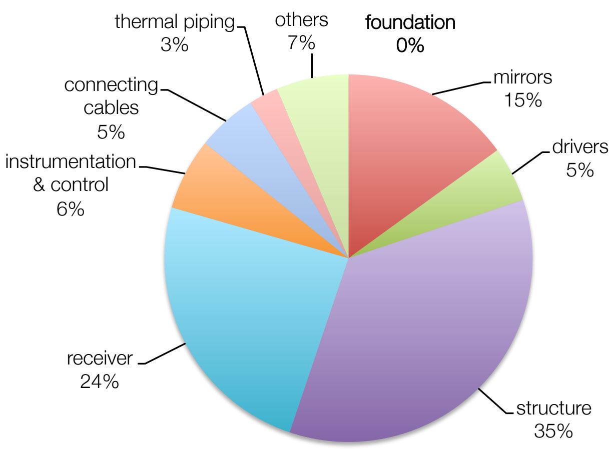


Figure 52 Cost breakdown

In this phase of the product development it is not yet possible to give a more precise cost estimation. Therefore more detail about the different components, hours for installation and logistical aspects are needed. What is clear though, is that the system will be more expensive due to the higher priority to make an aesthetically more attractive product than competitors over the low costs aspect.

14.12 Energy production

The most important function of the solar concentrator is to produce thermal and electrical energy. It depends on the location where the system is applied on how much energy can be produced each year. The total thermal efficiency in this stage of the project remains unknown, but by looking at other CST and CPVT low temperature systems an efficiency of 35% should be possible. For the electrical part all the efficiencies of the different components can be multiplied. As the field of application Naples is used as the location with field-pitch of 2.5 meters. This field is analyzed in Figure 36 which shows the shadowing factors and mismatch due to the concentrating function of the mirror. The factors that influence the efficiency are the optional glass plate, the reflectivity of the mirror and the efficiency of the PV cells and power inverter. The next figure shows a total electrical efficiency of 13.0%. Without glass plate the mirror needs a protective coating that decreases the mirror efficiency to 93%. The total efficiency will however increase to 13.9% when no glass plate in used. The thermal efficiency will drop in this case because of the isolating effect on the trough.

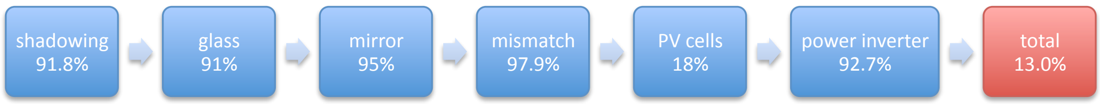


Figure 53 Electrical efficiency of the system

Naples has a direct solar energy of 1709 kWh/m^2 (PVsyst, 2010). A total minimum field area of around 6.5 x 11 m (with 1 meter of clearance around the field) has a total mirror area of 16 m^2. One system with eight modules will then produce 3540 kWh of electrical energy and around 9570 kWh of thermal energy per year. This is a combined system efficiency of 47.9%.

An average household of three persons uses around 3000 kWh on electricity a year (Sanoma Digital, 2010). A boiler uses around 9600 kWh a year on electricity including the production of this electricity via coal or gas and then transmitting it to the application sight. Using gas or oil directly to heat water reduces energy use for warm water to 3800 kWh a year (Greenpeace, 2010). Suppose a minimum field consisting of eight modules is applied on an average five floor high building in Naples with five households of three persons. Assuming two households use a boiler and the other ones use gas directly to heat the water, we get the following table.

	energy use	energy production	% self supplying
type	5 average households	field of 8 modules	
thermal energy	30,600 kWh	9,570 kWh	31%
electrical energy	15,000 kWh	3,540 kWh	24%

Table 7 Self supplying energy for an average application sight

It should be noted that these values are rough estimations of the energy use and production but it gives an idea of the potential of the system. In further development it is necessary to calculate these values more precisely. The system's potential to satisfy the demands of the European Union with the 20-20-20 targets is however clearly present by applying the product to appropriate buildings.

14.13 Renders

The following renders give a representation of different aspects of the hybrid solar concentrator. Notice the different colors that can be used for the ballast cover parts.

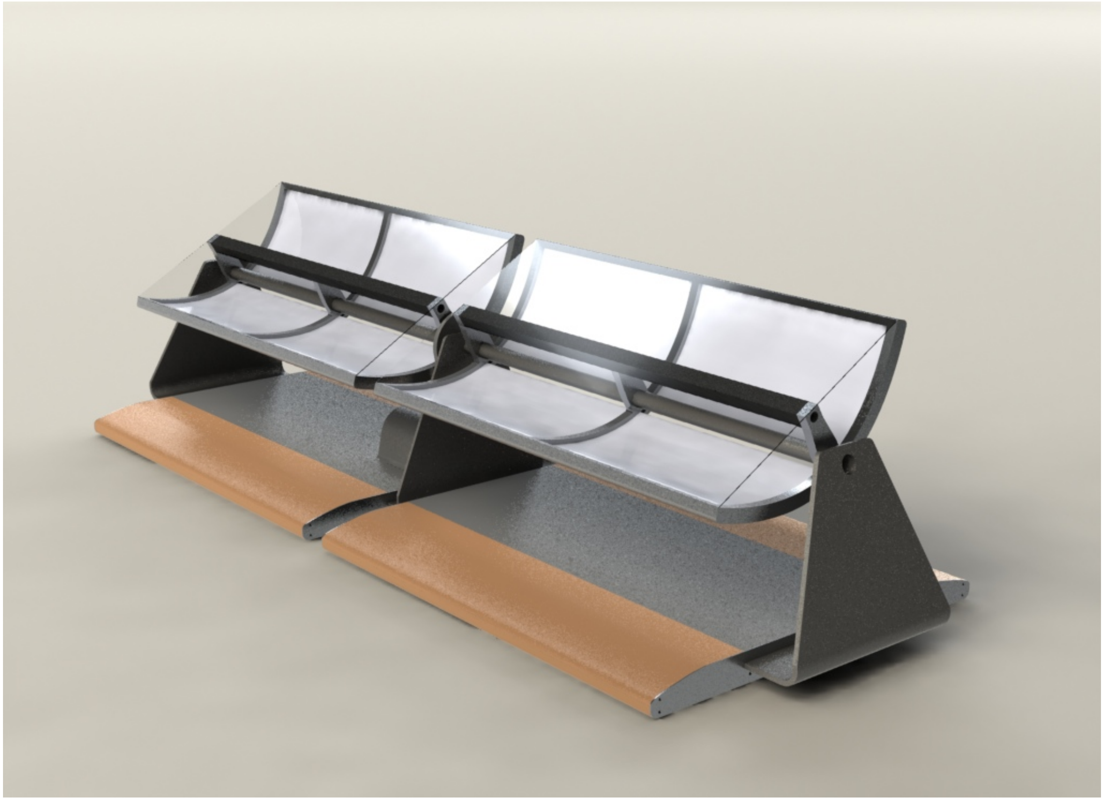


Figure 54 Render of two modules

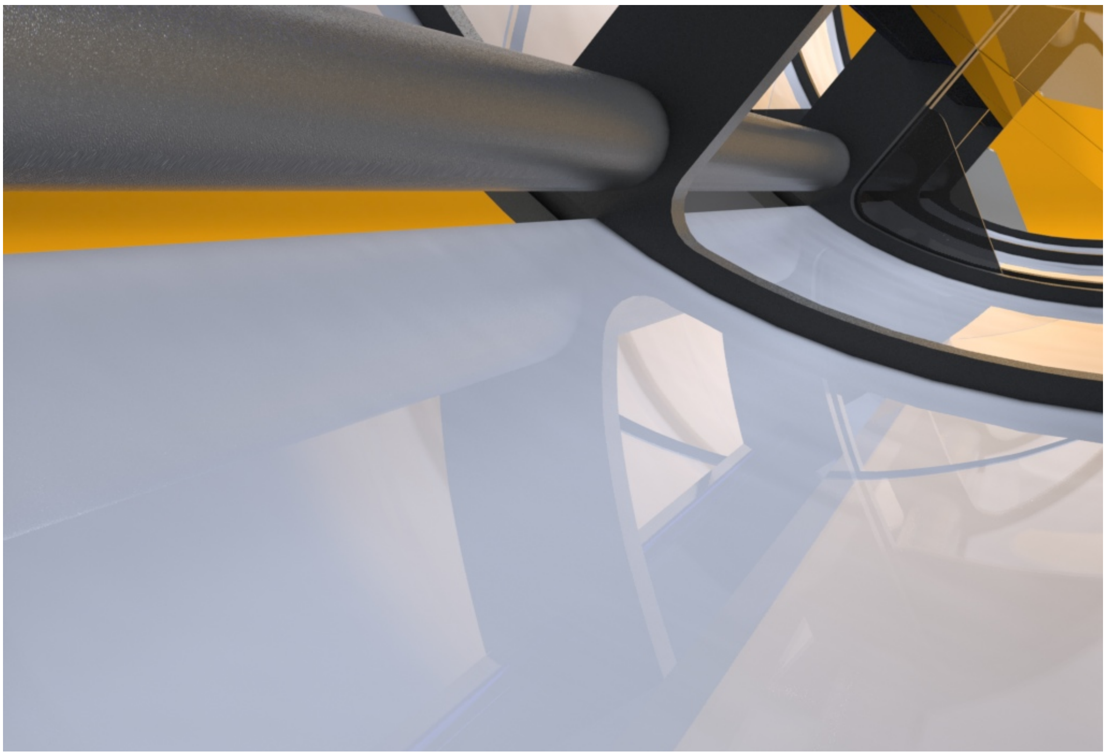


Figure 55 Render of rain drainage system if no glass cover is used

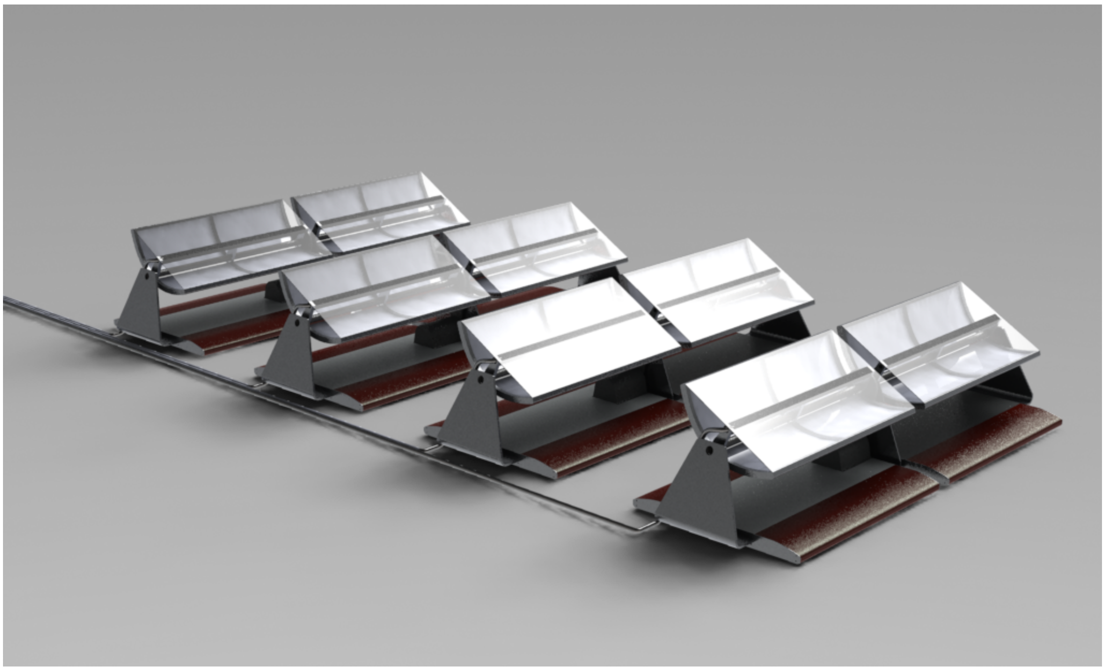


Figure 56 Render of a minimum field for one power inverter

Figure 57 Render of an example field of application

15. Conclusions and recommendations

The subject of this assignment was to design a single axis hybrid solar tracker that can be aesthetically integrated into building environments, has low production costs, a high optical efficiency and can easily be produced. For the largest part the final design succeeded in this assignment. Looking at the requirements from Figure 18 we can see that almost every requirement is fulfilled. There are however some requirements that need some explanation on the amount that they are fulfilled.

The production number range which is used to choose the production methods may be not correct. It depends on the market whether this number will be reached. For the assembly it is partly satisfying the requirement of pilling up sub-assemblies because the parabolic troughs require some extra support not to fall over in this case. Also the system is not fully plug and play because some assembly on the application sight is still needed and for the modularity there are coupling parts needed between the receivers which makes it more difficult to install. Because the receiver is still a part that has to be developed it is not yet known whether materials with enough thermal shock resistance are applied but it may be assumed they will. The tracking accuracy on the system is estimated by the engineers of ENEA and is expected to fall below the 0.5° deviation threshold. The most important requirement that is not fulfilled is to make the system low cost. An increase of over 25% with regard to competitors is estimated for the solar tracker which is a substantial increase. To aesthetically distinguish the product from comparable systems and by not allowing it to be mounted to the surface with a permanent connection, the product has are more expensive structure that contributes strongly to this increase.

The next figure shows a comparison of the solar tracker to the other hybrid solar concentrators currently commercially available on the market. As can be seen it has comparable performance but it distinguishes itself by being a flexible system that can be aesthetically integrated into building environments. This is at the cost of being heavier and more expensive but almost no adjustment to the application surface is needed to install the system which is a major advantage. The system's potential to satisfy the demands of the European Union with the 20-20-20 targets is high by applying the product to appropriate buildings.

	1	2	3
General information			
Manufacturer	Absolicon	Power-Spar	ENEA
Country	Sweden	Canada	Italy
Product name	X10	PS-35	Solar Concentrator
System type	CPVT Parabolic trough	CPVT Power tower	CPVT Parabolic trough one unit
Year of introduction	2007	NA	2010
Performance			
LCOE ($/kWh)	NA	NA	NA
Peak power (Wp)	550	6500	720
Electrical energy (kWh/m²/y)	120	270	220
Thermal energy (kWh/m²/y)	750	560	600
Solar radiance (kWh/m²/y)	1800	1800	1709
Efficiency	48%	46%	48%
Technical aspects			
Dimensions per unit (wxd) (m)	1.1 x 6	7.3 x 6.8	1.60 x 4.50
Weight per unit (kg)	195	1600	700
Tracking system			
Solar tracker type	Single axis	Dual axis	Single axis
Tracking of sun by	GPS	NA	GPS
Accuracy	NA	NA	+/- 0.5°
Other			
Mirror material	Aluminum	NA	Aluminum
Cooling type	Fluid	Fluid	Fluid Water

Figure 58 Comparison of final product to competitors

In the future development the optimization of parts to lower the costs will be a major aspect. Not only the parts can be designed more efficient but also the production methods can be optimized and maybe simplified. Also in this stage the receiver has to be developed so that better estimations on costs and performance can be made, especially for the thermal part of the energy production. To make the system more flexible, alternative solutions have to be found for the currently used power inverter which limits the minimum (extra) field size. Then with some prototyping and testing the estimations on costs and energy production can be tested and improved so that a production ready stage can be reached.

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Appendices

A. Datasheets Omron Accurax G5 10030H electromotor

OMRON

Servo motor specifications

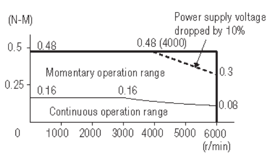
Servo motors 3000 r/min, 230 V

Ratings and specifications

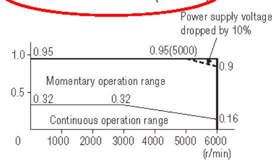
	Voltage		230 V						
	Servo motor model R88M-K☐	20-bit incremental encoder	**05030H-☐**	**10030H-☐**	**20030H-☐**	**40030H-☐**	**75030H-☐**	**1K030H-☐**	**1K530H-☐**
		17-bit absolute encoder	**05030T-☐**	**10030T-☐**	**20030T-☐**	**40030T-☐**	**75030T-☐**	**1K030T-☐**	**1K530T-☐**
	Rated output	W	50	100	200	400	750	1000	1500
	Rated torque	N·m	0.16	0.32	0.64	1.3	2.4	3.18	4.77
	Instantaneous peak torque	N·m	0.48	0.95	1.91	3.8	7.1	9.55	14.3
	Rated current	A (rms)	1.2	1.1	1.5	2.4	4.1	6.6	8.2
	Instantaneous max. current	A (rms)	5.1	4.7	6.5	10.2	17.4	28	35
	Rated speed	min^{-1}	3000						
	Max. speed	min^{-1}	6000					5000	
	Torque constant	N·m/A (rms)	0.11±10%	0.21±10%	0.31±10%	0.39±10%	0.42±10%	0.37	0.45
	Rotor moment of inertia (JM)	$kg·m^2x10^{-4}$ (without brake)	0.025	0.051	0.14	0.26	0.87	2.03	2.84
		$kg·m^2x10^{-4}$ (with brake)	0.027	0.054	0.16	0.28	0.97	2.35	3.17
	Allowable load moment of inertia (JL)	Multiple of (JM)	30				20	15	
	Rated power rate	kW/s (without brake)	10.1	19.9	29.0	62.4	65.6	49.8	80.1
		kW/s (with brake)	9.4	18.8	25.4	58	58.8	43	71.8
	Allowable radial load	N	68		245		490		
	Allowable thrust load	N	58		98		196		
	Approx. mass	Kg (without brake)	0.32	0.47	0.82	1.2	2.3	3.5	4.4
		Kg (with brake)	0.53	0.68	1.3	1.7	3.1	4.5	5.4
Brake specifications	Rated voltage		24VDC ±10%						
	Holding brake moment of inertia J	$kg·m^2x10^{-4}$	0.002		0.0018		0.33		
	Power consumption (at 20°C)	W	7		9		17	19	
	Current consumption (at 20°C)	A	0.3		0.36		0.70±10%	0.81±10%	
	Static friction torque	N.m (minimum)	0.29		1.27		2.5	7.8	
	Rise time for holding torque	ms (max.)	35		50				
	Release time	ms (max)	20		15				
Basic specifications	Time Rating		Continuous						
	Insulation class		Type B					Type F	
	Ambient operating/ storage temperature		0 to +40°C/ -20 to 65°C						
	Ambient operating/ storage humidity		20 to 80% (non-condensing)					20 to 85% (non-condensing)	
	Vibration class		V-15						
	Insulation resistance		20 MΩ min. at 500 VDC between the power terminals and FG terminal						
	Enclosure		Totally-enclosed, self-cooling, IP67 (excluding shaft opening)						
	Vibration resistance		Vibration acceleration 49 m/s2						
	Mounting		Flange-mounted						

Torque-speed characteristics

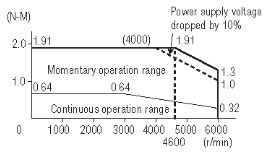
R88M-K05030H/T (50 W)



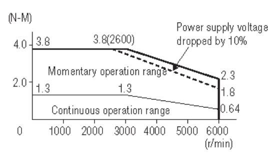
R88M-K10030H/T (100 W)



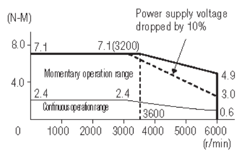
R88M-K20030H/T (200 W)



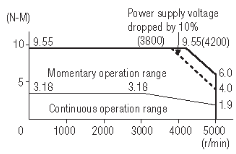
R88M-K40030H/T (400 W)



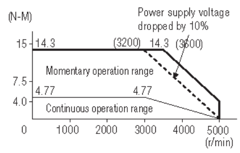
R88M-K75030H/T (750 W)



R88M-K1K030H/T (1 kW)



R88M-K1K530H/T (1.5 kW)



AC Servo systems

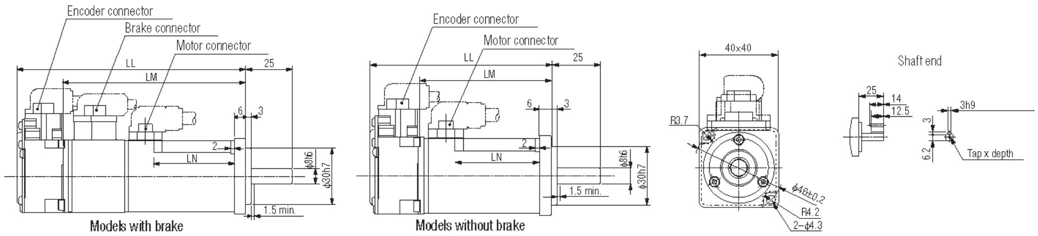
Figure 59 Datasheet 1 Omron Accurax G5 10030H

Dimensions

Servomotors

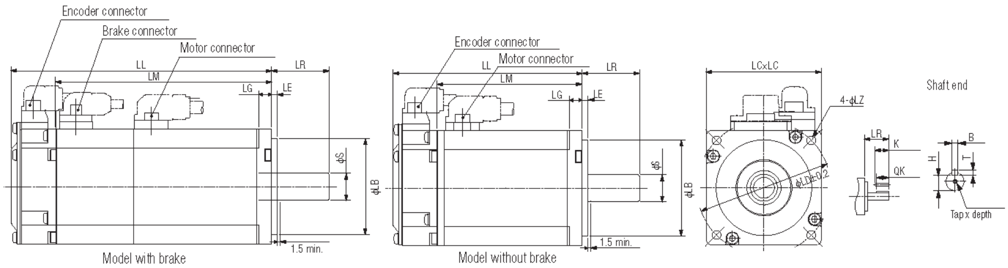
Type 3000 r/min motors (230 V, 50 - 100 W)

Dimensions (mm)	Without brake		With brake		LN	Shaft End Dimensions	Approx. Mass (Kg)	
Model	LL	LM	LL	LM		Tap × Depth	Without brake	With brake
R88M-K05030(H/T)-□S2	72	48	102	78	23	M3 x 6L	0.32	0.53
R88M-K10030(H/T)-□S2	92	68	122	98	43		0.47	0.68



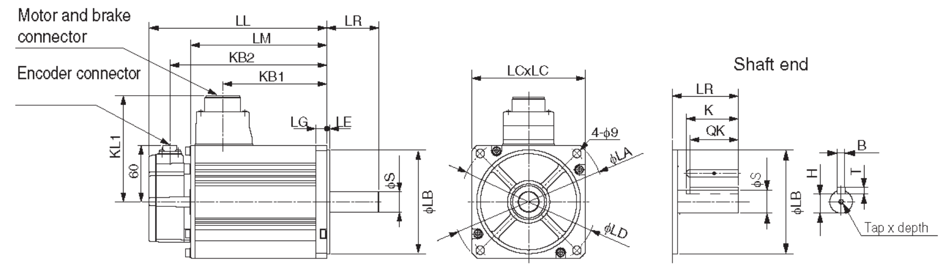
Type 3000 r/min motors (230 V, 200 - 750 W)

Dimensions (mm)	Without brake		With brake		LR	Flange surface						Shaft End Dimensions							Approx. Mass Kg	
Model	LL	LM	LL	LM		LB	LC	LD	LE	LG	LZ	S	K	QK	H	B	T	Tap × Depth	Without brake	With brake
R88M-K20030(H/T)-□S2	79.5	56.5	116	93	30	50^{h7}	60	70	3	6.5	4.5	11^{h6}	20	18	8.5	4^{h9}	4	M4x8L	0.82	1.3
R88M-K40030(H/T)-□S2	99	76	135.5	112.5								14^{h6}	25	22.5	11	5^{h9}	5	M5x10L	1.2	1.7
R88M-K75030(H/T)-□S2	112.2	86.2	148.2	122.2	35	70^{h7}	80	90		8	6	19^{h6}		22	15.5	6^{h9}	6		2.3	3.1



Type 3000 r/min motors (230 V, 1 - 1.5 kW/ 400V, 750 W - 5 kW)

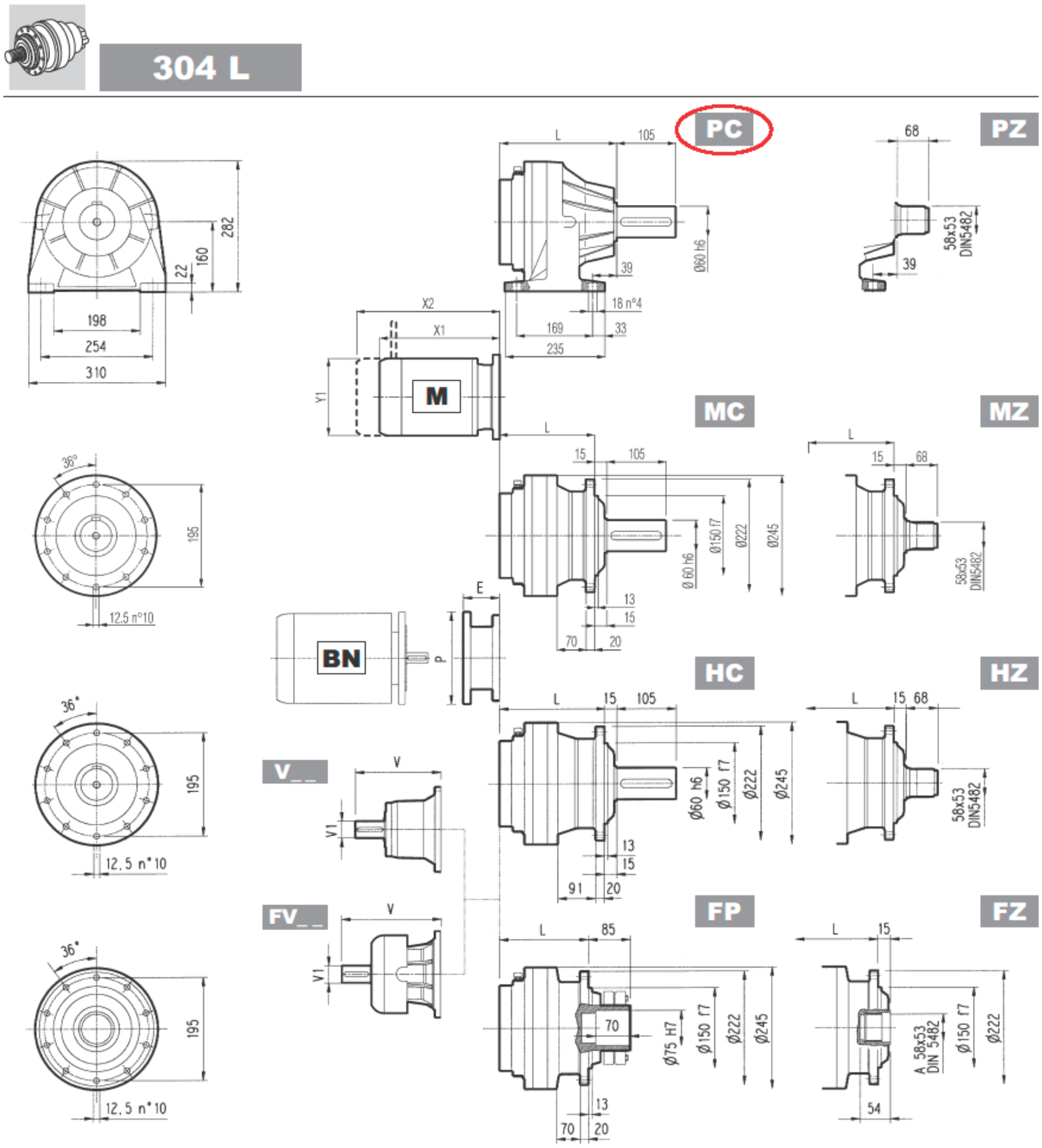
Dimensions (mm)		Without brake					With brake					LR	Flange surface						Shaft End Dimensions							Approx. Mass (Kg)	
Voltage	Model R88M-K□	LL	LM	KB1	KB2	KL1	LL	LM	KB1	KB2	KL1		LA	LB	LC	LD	LE	LG	S	Tap x Depth	K	QK	H	B	T	Without brake	With brake
230	1K030(H/T)-□S2	141	97	66	119	101	168	124	66	146	101	55	135	95^{h7}	100	115	3	10	19^{h6}	M5x 12L	45	42	15.5	6^{h9}	6	3.5	4.5
	1K530(H/T)-□S2	159.5	115.5	84.5	137.5		186.5	142.5	84.5	164.5																4.4	5.4
400	75030(F/C)-□S2	131.5	87.5	56.5	109.5		158.5	114.5	53.5	136.5	103															3.1	4.1
	1K030(F/C)-□S2	141	97	66	119		168	124	63	146																3.5	4.5
	1K530(F/C)-□S2	159.5	115.5	84.5	137.5		186.5	142.5	81.5	164.5																4.4	5.4
	2K030(F/C)-□S2	178.5	134.5	103.5	156.5		205.5	161.5	100.5	183.5																5.3	6.3
	3K030(F/C)-□S2	190	146	112	168	113	215	171	112	193	113		162	110^{h7}	120	145		12	22^{h6}			41	18	8^{h9}	7	8.3	9.4
	4K030(F/C)-□S2	208	164	127	186	118	233	189	127	211	118	65	165		130		6		24^{h6}	M8x 20L	55	51	20			11	12.6
	5K030(F/C)-□S2	243	199	162	221		268	224	162	246																14	16



AC Servo systems

Figure 60 Datasheet 2 Omron Accurax G5 10030H

B. Datasheet Bonfiglioli 304 L4 1018 reduction gear



FP	M_{2max} = 6000 Nm

	L				Kg																
	MC - MZ	PC - PZ	HC - HZ	FP - FZ	MC - MZ	PC - PZ	HC - HZ	FP - FZ	V	V1	Kg	V	V1	Kg	V	V1	Kg	V	V1	Kg
304 L1	125	165	150	125	31	40	35	31	239	48	15	-	-	-	276	48	17	-	-	-
304 L2	190	230	215	190	38	47	42	38	137.5	24	6	158	38	7	-	-	-	-	-	-
304 L3	243	283	268	243	42	51	46	42	137.5	24	6	158	38	7	-	-	-	-	-	-
304 L4	296	336	321	296	46	55	50	46	137.5	24	6	158	38	7	-	-	-	-	-	-

	P71		P80		P90		P100		P112		P132		P160		P180		P200	
	E	P	E	P	E	P	E	P	E	P	E	P	E	P	E	P	E	P
304 L1	-	-	-	-	-	-	-	-	-	-	114	300	144	350	144	350	174	400
304 L2	65	160	84	200	84	200	94	250	94	250	114	300	144	350	-	-	-	-
304 L3	65	160	84	200	84	200	94	250	94	250	114	300	144	350	-	-	-	-
304 L4	65	160	84	200	84	200	94	250	94	250	114	300	144	350	-	-	-	-

	S1 + M1S			S1 + M1L			S2 + M2S			S3 + M3S			S3 + M3L			S4 + M4			S5 + M5S			S5 + M5L		
	X1	X2	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2	Y
304 L1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	460	571	258	552	692	310	596	736	310
304 L2	229	292	138	253	314	138	280	352	156	325	421	195	357	449	195	460	571	258	-	-	-	-	-	-
304 L3	229	292	138	253	314	138	280	352	156	325	421	195	357	449	195	460	571	258	-	-	-	-	-	-
304 L4	229	292	138	253	314	138	280	352	156	325	421	195	357	449	195	460	571	258	-	-	-	-	-	-

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BONFIGLIOLI TRASMITAL

Figure 61 Datasheet Bonfiglioli 304 L4 1018

C. Datasheet Fronius IG 30 power inverter

OVERVIEW OF THE FRONIUS **IG** FAMILY.

It goes without saying that every Fronius IG complies with all the obligatory guidelines and standards.
More in-depth information and certificates may be viewed at www.fronius.com under 'downloads'.
Of course, all Fronius IG bear the CE mark.

INPUT DATA	Fronius **IG** 15	20	30	40	60 HV
MPP voltage range	150 - 400 V	150 - 400 V	150 - 400 V	150 - 400 V	150 - 400 V
Max. input voltage (at 1000 W/m²; -10°C)	500 V	500 V	500 V	500 V	530 V
PV system output	1300 - 2000 Wp	1800 - 2700 Wp	2500 - 3600 Wp	3500 - 5500 Wp	4600 - 6700 Wp
Max. input current	10,8 A	14,3 A	19,0 A	29,4 A	35,8 A

OUTPUT DATA	Fronius **IG** 15	20	30	40	60 HV
Nominal output	1300 W	1800 W	2500 W	3500 W	4600 W
Max. power output	1500 W	2000 W	2650 W	4100 W	5000 W
Max. efficiency	94,2 %	94,3 %	94,3 %	94,3 %	94,3 %
Euro efficiency	91,4 %	92,3 %	92,7 %	93,5 %	93,5 %
Mains voltage / frequency			230 V / 50 Hz (60 Hz)		
Distortion factor			< 3,5 %		
Power factor			1		
Power consumption at night			0 W		

GENERAL DATA	Fronius **IG** 15	20	30	40	60 HV
Size (l x w x h)		366 x 344 x 220 mm (500 x 435 x 225 mm)			610 x 344 x 220 mm (733 x 435 x 225 mm)
Weight		9 kg (12 kg)			16 kg (20 kg)
Cooling			controlled forced-air cooling		
Housing variations			designer internal housing; optional outdoor housing		
Ambient temperature range			-20 ..... 50 °C		
Permissible humidity			0 ..... 95 %		

PROTECTIVE DEVICES	Fronius **IG** 15	20	30	40	60 HV
DC insulation measurement			warning when R_{ISO} < 500k Ohm		
Polarity reversal protection			built-in		
Behaviour on DC overload			displacement of operating point		

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Figure 62 Datasheet Fronius IG 30

D. FEM analysis

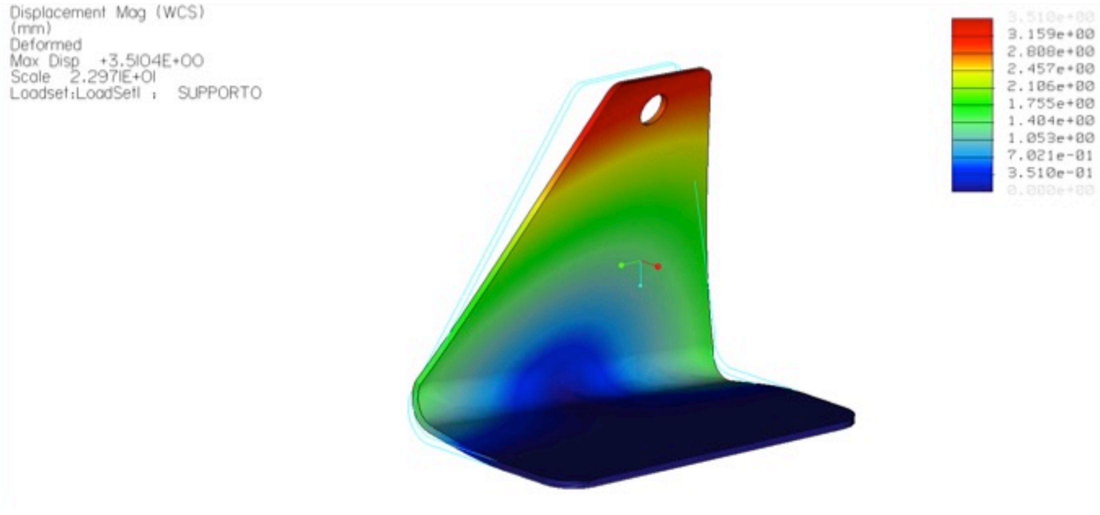

Figure 63 Displacement of the 15mm thick aluminum shaft supporting side part (Pro/ENGINEER 5.0)

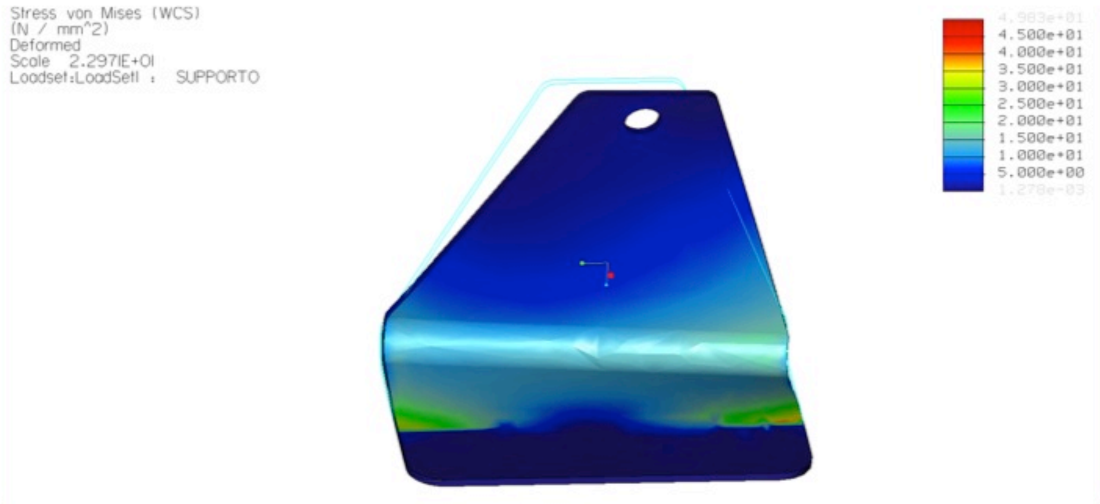

Figure 64 Stress on the 15mm thick aluminum shaft supporting side part (Pro/ENGINEER 5.0)

E. CES Edupack 2009

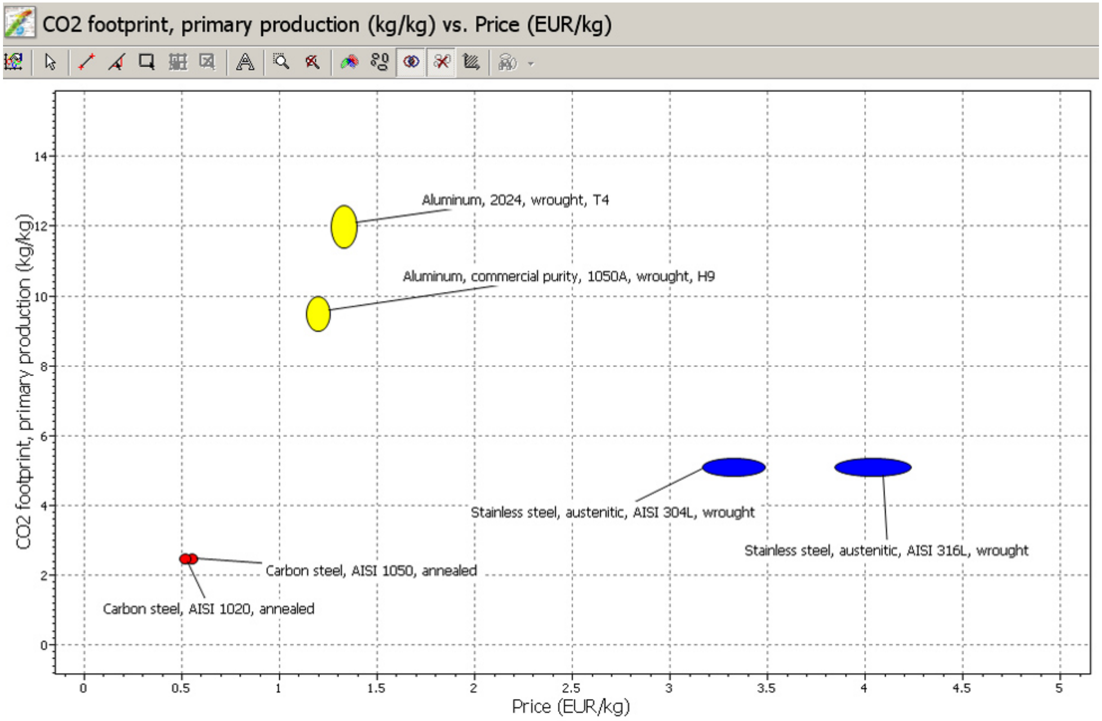

Figure 66 Price versus CO_2 footprint of aluminum, stainless steel and carbon steel

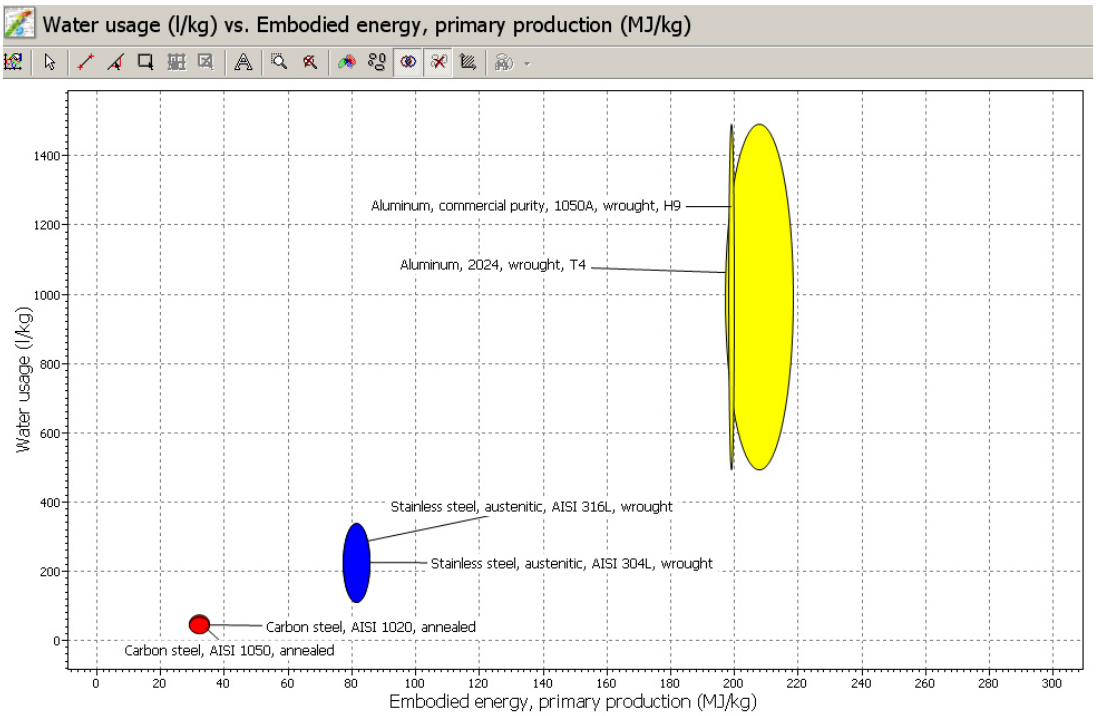

Figure 65 Embodied energy versus water usage of aluminum, stainless steel and carbon steel

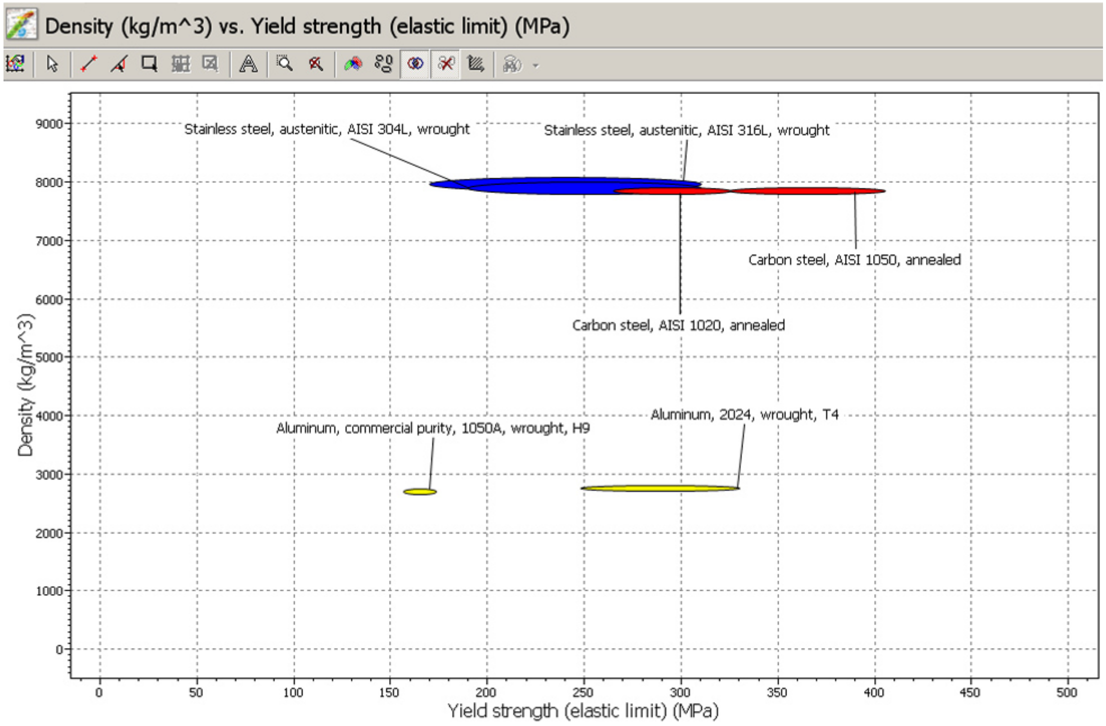

Figure 67 Yield strength versus density of aluminum, stainless steel and carbon steel

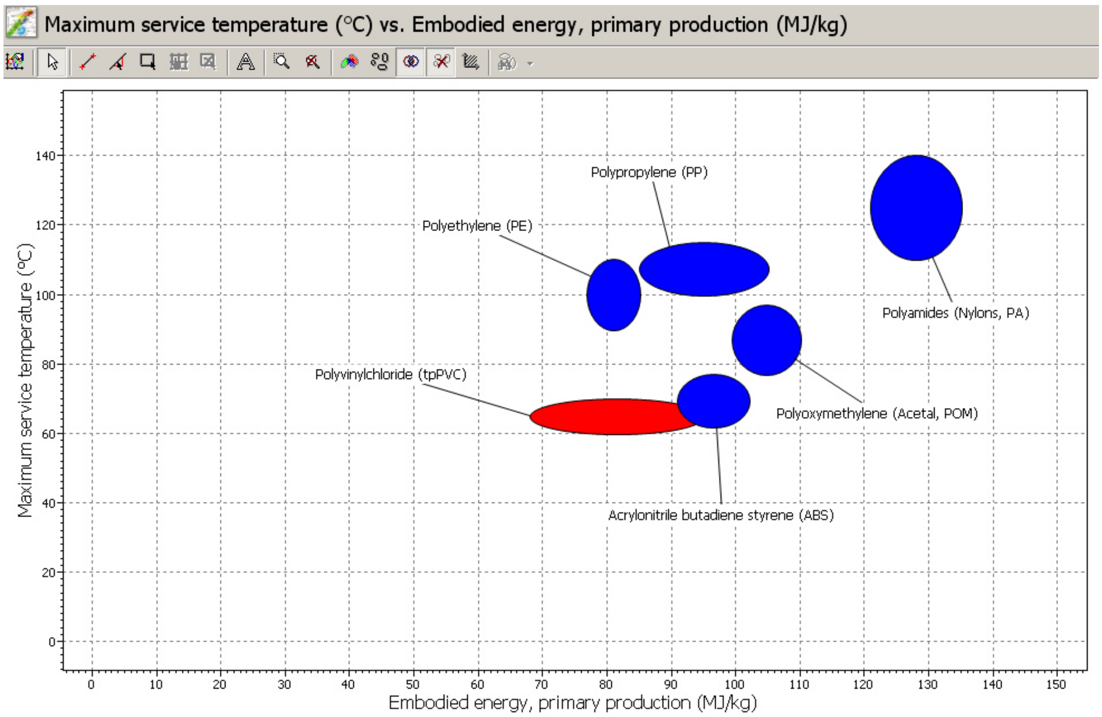

Figure 68 Embodied energy versus maximum service temperature of different polymers

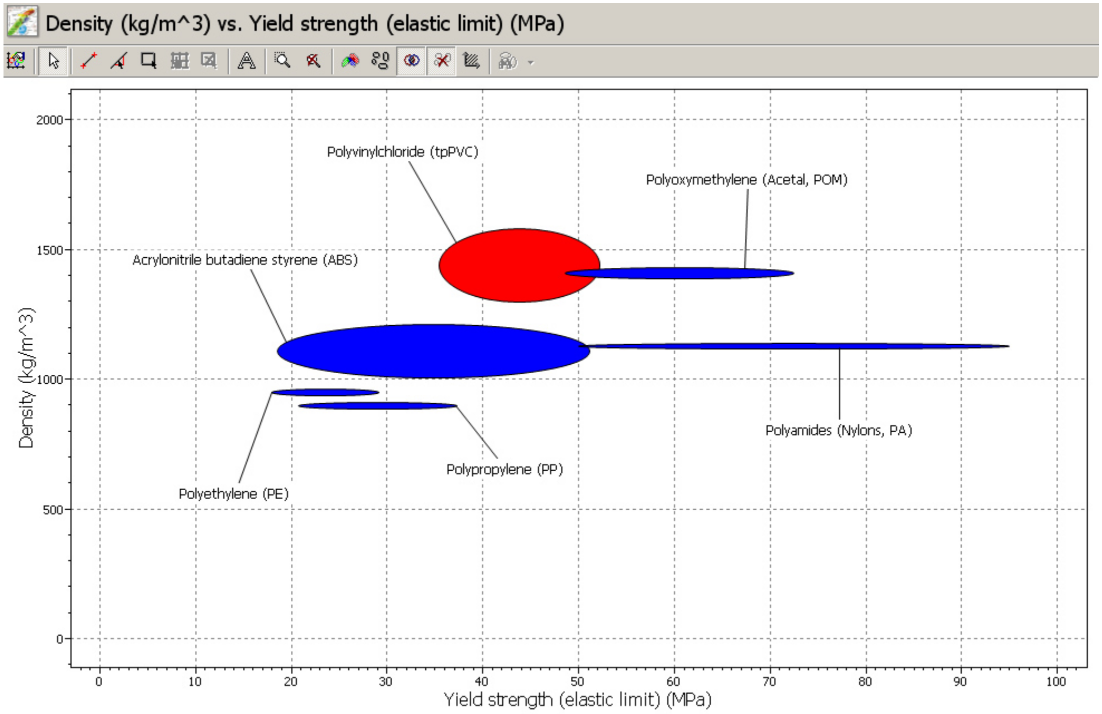

Figure 69 Yield strength versus density of different polymers

Project Plan

Development of a single axis tracker for a hybrid solar system

Reinier ter Welle - s0118168 – r.terwelle-1@student.utwente.nl - +31 6 3040 9646 – 17-04-2010

ENEA

UNIVERSITY OF TWENTE.

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Actor analysis

The activities of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) are targeted to research, innovation technology and advanced services in the fields of energy and sustainable economic development. ENEA is mainly financed by government grant and gains from program activities. The public agency has a total staff of around 3.000 employees located at different offices and research centers all around Italy (ENEA, 2010).

One of ENEA's objectives is to accelerate the technological development of limited eco-impact energy systems. In line with this objective, many projects covering several different fields have been started up, with a view to keep the country system's competitivity high in the framework of sustainable development.

The specific research centre of ENEA in this case is the Portici Research Center, which among others, focuses on the development of concentrating solar power (CSP) systems. In such a system solar radiation is gathered by a solar collector to convert it directly to electrical power (photovoltaics) or to heat a fluid in a receiving tube (solar thermal power). The heated fluid can be used as an energy source for all kinds of applications. The solar thermodynamic energy objectives are to set up pilot plants – where high-temperature energy is produced by means of concentrating solar power systems – for the production of electric power through steam driven turbines, seawater desalination, and heat and cold generation for civil and industrial uses (ENEA Portici Research Centre, 2010).

Project framework

ENEA has a long and recognized experience in the development of photovoltaic (PV) technologies and in particular on concentrating PV systems, as becomes clear from the Photovoltaic Concentrators to Utility Scale (PhoCUS) project (ENEA, 2010). To support the achievement of a leadership position in some specific CSP technologies ENEA started the 'Archimede' project together with Enel; Italy's largest power company. The main goal of the Archimede project is the realization and commercial operation (by Enel) of a demonstration plant using the technology developed by ENEA to be integrated in a combined cycle standard power plant. ENEA hopes this plant will start the realization of a number of solar systems using the ENEA technology (Maccari, 2008), (ESTEEM, 2010).

Based on the knowledge from both projects, ENEA started a program for the development of hybrid photovoltaic and thermal concentrating system. The focus of the work is the design of a single axis solar tracker with the following features:

- very high optical efficiency
- low production cost
- attractive design for building integration

This activity must lead to the development of a mechatronic prototype that potentially can be further commercialized helping ENEA getting a prominent position in the development of concentrating hybrid solar systems.

Objective

The target of the assignment is to help ENEA getting a prominent position in the development of concentrating hybrid solar systems by improving the current technology in order to develop an effective, low-cost, robust single axis tracker that can be easily produced and aesthetically integrated in building environments.

This will be done by first analysing from which parts the existing single axis tracking system and supporting structure that are currently used, is built up and how the system works and is maintained. After that an analysis of the costs of the parts, assembly, operation, maintenance and other aspects after installation will be made. An overview will be made from the fields of application of the solar thermal systems. From this information the problems with the single axis tracker can be cleared out and a list of preferences and requirements can then be made. Alternatives for the parts will be sought or designed. The possibility to add different parts together into one part will be considered during the design process.

The PV cells and thermal receiver tube will not be a part of the project. The end result will be a design proposal in the form digital 3D model and a form model that can be used for the development of a mechatronic prototype of an innovative hybrid solar PV-thermal system. The assignment will be carried out in a period of 3 months.

References

ENEA, 2010, http://www.enea.it/com/ingl/default.htm, accessed 8 apr. 2010

ENEA Portici Research Centre, 2010, http://www.enea.it/com/ingl/center/Portici_Research_Centre.pdf, accessed 8 apr. 2010

ESTEEM, 2010, http://www.esteem-tool.eu/fileadmin/esteem-tool/docs/Archimede.pdf, accessed 8 apr. 2010

Maccari, A., 2008, "The ENEA's Way to Concentrating Solar Power", *Solar Innovation Today*, http://www.twanetwerk.nl/upl_documents/ENEAMaccari.pdf, accesses 8 apr. 2010

Research questions

1 How is the current single axis tracker built up?
   a. What are the main components?
   b. What are the detailed sub-components?
   c. How are the components related to each other?

2 How does the current single axis tracker work?
   a. Which techniques are used?
   b. How does the solar-energy conversion take place?
   c. How do the different parts work?

3 What are the costs of a single axis tracker and what are the bottlenecks in these costs?
   a. What are the stakeholders involved in the single axis tracker?
   b. What are the production costs of the sub-components?
   c. What are the assembly costs?
   d. What are the installation, maintenance and operational costs?
   e. What are the bottlenecks in the costs from the point of view of ENEA?
   f. Which components can be replaced with cheaper alternatives without affecting the performance?
   g. Which components can be combined or redesigned for cost reduction?

4 What are the fields of application of hybrid solar systems?
   a. What are the current fields of application of hybrid solar systems?
   b. What are potential fields of application of hybrid solar systems?

5 What are the preferences and requirements for the single axis tracker?
   a. What are the cost related preferences and requirements?
   b. What are the mechanical preferences and requirements?
   c. What are the production related preferences and requirements?
   d. What are the aesthetically related preferences and requirements?
   e. What are the preferences and requirements from the fields of application?

6 What are the designed concepts and which one will be further developed?
   a. How are the different components (re)designed in the different concepts?
   b. What are the estimated costs for the designed concepts?
   c. To what extent do the different concepts satisfy the preferences and requirements?
   d. Which concept is the best, looking at the preferences and requirements?
   e. Which concept is the best from the point of view of ENEA?

7 What is the end result?
   a. What are the different components (i.e. how do they look like, how do they work and which materials are used)
   b. How are the components produced?
   c. How are the components assembled (on site)?
   d. What are the estimated costs for the new single axis tracker?
   e. To what extent does the end result satisfies the preferences and requirements?
   f. How does the digital 3D model look like?
   g. How does the form model look like?

Definition of terms

country system's competitivity

The potential to have a certain amount of influence in the development in a certain field, in this case the sustainable development.

mechatronic prototype

A full-scale fully operational prototype.

form model

A model created to show the external form of the end result. It's only made for visual purposes and has limited or no functional aspects.

ESTEEM tool

A step-by-step toolbox for sustainable energy projects which among others analyses the stakeholders involved in the project. It has already been applied to the Archimede project.

Strategy and research material

Question		Strategy	Source	How
1	How is the current single axis tracker built up?	Product research	Single axis tracker	Analysing the product
			Documents	Analysing construction drawings
2	How does the current single axis tracker work?	Product research	Single axis tracker	Analysing the product
			Persons	Expert reviews
			Literature	Articles about solar thermal systems
3	What are the costs of a single axis tracker and what are the bottlenecks in these costs?	Cost analysis	Documents	Purchase specifications, component lists, documents ESTEEM tool
			Persons	Interviews with people of the purchase department, expert reviews
		Bottlenecks analysis	Persons	Interviews with people of different disciplines of ENEA
			Single axis tracker	Analysis of bottlenecks via product and component cost analysis
			Documents	
4	What are the fields of application of hybrid solar systems?	Observation	Surroundings and media	Looking in environment and doing research on the internet
		Literature research	Literature	Articles about hybrid solar systems
5	What are the preferences and requirements for the single axis tracker?	Interview	Persons	Interviews with people from ENEA
		Literature research	Literature	Concluding mechanical requirements and doing calculations
6	What are the designed concepts and which one will be further developed?	Design	Media	Drawings, prototypes, digital models
		Cost estimation	Interview	Design- and engineering experts ENEA
		Interview	Persons	Interview with ENEA experts
		Analysis	Literature	Compare the concepts with the list of preferences and requirements
7	What is the end result?	Design	Product	Digital and form models, drawings, prototypes
		Cost estimation	Interview	Design- and engineering experts ENEA and University of Twente
		Analysis	Literature	Compare the end result with the list of preferences and requirements

Planning

(A Gantt Chart of this planning is also available as an extra document)

	Phase	Start date	End date	Lead time (days)
1	analysing phase	26-04-2010	16-05-2010	21
1.1	analysing the parts of the product	26-04-2010	28-04-2010	3
1.2	analysing how the product works	28-04-2010	03-05-2010	6
1.3	analysing current and potential fields of application	29-04-2010	07-05-2010	9
1.4	stakeholder analysis	03-05-2010	07-05-2010	5
1.5	analysing the all the costs of the product	03-05-2010	14-05-2010	12
1.6	analysing the bottlenecks in the costs	10-05-2010	14-05-2010	5
1.7	analysing which components can be replaced with cheaper alternatives	08-05-2010	14-05-2010	7
1.8	analysing which components can be combined or redesigned for cost reduction	08-05-2010	14-05-2010	7
1.9	documentation	07-05-2010	16-05-2010	10
2	preferences and requirements	03-05-2010	23-05-2010	21
2.1	application related preferences and requirements	03-05-2010	11-05-2010	9
2.1	cost related preferences and requirements	10-05-2010	16-05-2010	7
2.3	production related preferences and requirements	12-05-2010	23-05-2010	12
2.4	mechanical related preferences and requirements	12-05-2010	23-05-2010	12
2.5	aesthetically related preferences and requirements	12-05-2010	23-05-2010	12
2.6	documentation	19-05-2010	23-05-2010	5
3	concept development	19-05-2010	13-06-2010	26
3.1	redesign the parts to be cheaper and easier to assemble	19-05-2010	08-06-2010	21
3.2	estimate the costs of redesigned concepts	03-06-2010	10-06-2010	8
3.3	reflect concepts to preferences and requirements	03-06-2010	10-06-2010	8
3.4	concept choice	07-06-2010	13-06-2010	7
3.5	documentation	09-06-2010	13-06-2010	5
4	product design	14-06-2010	15-08-2010	63
4.1	redesign of (combined) parts to optimize product	14-06-2010	27-06-2010	14
4.2	make digital 3d model	21-06-2010	04-07-2010	14
4.3	estimate costs of product	30-06-2010	06-07-2010	7
4.4	reflect product design to preferences and requirements	05-07-2010	06-07-2010	2
4.5	make form model at the University of Twente	26-07-2010	08-08-2010	14
4.6	documentation	28-06-2010	06-07-2010	9
5	finalize concept report	05-07-2010	18-07-2010	14
6	making final report	26-07-2010	08-08-2010	14

Points of attention

Strategy / task	Bottlenecks	Solution
Expert reviews and interviews ENEA	Availability experts	Use information that tutor has collected
		Literature research
		Flexibility in planning
Cost estimation	Available information	Make estimation with engineering department
Form models	Materials needed on time	Make an inventory and order materials in the Netherlands already from Italy
	Availability workshop and machines	Extend lead time