SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Solar Collector Systems

https://doi.org/10.52825/solarpaces.v3i.2422

Published: 24 Sep. 2025

Automated Heliostat Installation

Pile Driving and Efficient Material Flow for Reduced Heliostat Field Cost

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Abstract. A concept for the automated installation of heliostats for solar tower power plants was developed with the primary objective of reducing installation costs. Following a discussion on the various types of foundations available for installation, the pile foundation was selected on account of its favourable cost per heliostat. The feasibility of this approach was assessed by calculating the wind loads and the structural stability. Vibratory pile driving was selected as the method for driving the pylons into the ground, as it enables the pile driving of very thin-walled pylons with minimal stress on the component. The installation of a heliostat is a two-step process, involving the piling of the pylons and the subsequent fastening of the concentrator with the tracking device. The fastening is facilitated by thin sheet metal screws, which were determined to be the optimal joining method, considering the requirements. In order to facilitate the efficient transportation of the components and the subsequent installation of several thousand heliostats on the solar field, various installation and material flow concepts were developed and evaluated, with particular attention to the resulting installation cost. Consequently, vehicle concepts for the automatic execution of the two process steps and for the material transport were derived and a design proposal is presented: The first is a heavy tracked vehicle for the purpose of pylon piling, and the second is two smaller vehicles for transporting and assembling the concentrators, with tracking devices.

Keywords: Central Receiver, Concentrator, Heliostat, Installation, Cost

1. Introduction

In the context of the global energy transition, which is being driven by the need to address climate change and the associated move away from fossil fuels, there is an increasing focus on the development of renewable energy sources. In addition to wind power, solar energy is a pivotal component in the pursuit of an emission-free energy supply. Solar tower systems represent a significant technological advancement, particularly in the generation of heat at high temperatures. The solar field for concentrating sunlight is formed by biaxially tracked mirrors, known as heliostats.

Heliostats are usually assembled on site. This is particularly the case with larger heliostats. The objective of reducing costs is best achieved by means of series production and factory assembly, a practice that is already well possible for smaller heliostats. However, the size of fully assembled heliostats, even of the smallest models, poses a challenge to cost-efficient shipping in overseas containers. This necessitates the preliminary assembly of sub-assemblies, which then require full assembly on site or during installation. For larger heliostats, concrete foundations are generally utilised. For smaller models, ground anchors are more likely to be applied. However, alternative concepts have been proposed. These include heavy bases, which connect the heliostats to each other to form a large frame construction that withstands wind loads due to its own weight and the large base area, and the insertion of piles.

The solar field accounts for approximately 40 percent of the total cost of a solar tower system [1]. Reducing the size of the heliostats increases their efficiency [2] and reduce costs [3]. However, increasing the number of heliostats also increases the installation effort. In order to reverse this counter-productive effect, it is useful to aim for a fully automated installation to further reduce costs. Achieving this objective necessitates the determination of the ground anchoring method and the configuration of the autonomous vehicle. The transportation of components to the solar field must be efficient, and all installation processes must be executed with precision. The following sections will discuss the available options. The cost-optimal combination for a sample heliostat [2] (see Figures 1 and 5, left) will be determined. Wireless communication and energy supply are assumed, so no field wiring is required. The site preparation, which is contingent on the conditions at the site [4], is not considered in this study. This study is, to the authors' knowledge, the first of its kind to be published.

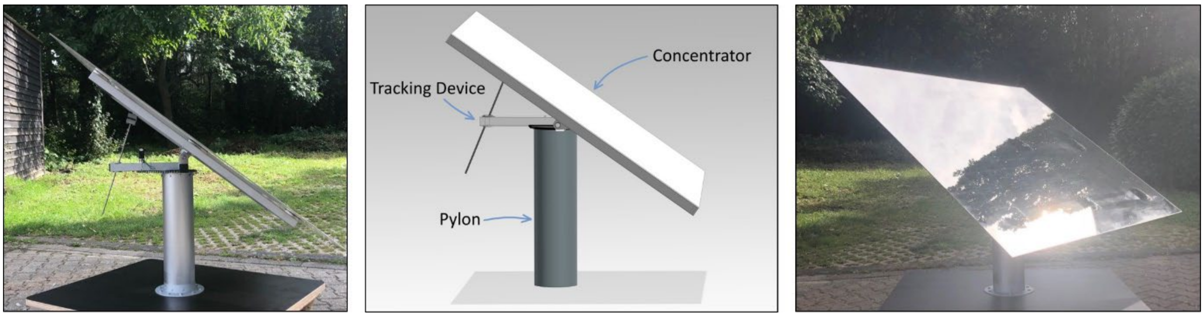

Figure 1. *DLR heliostat [2] for automated field installation*

2. Pile driving

2.1 Foundation concepts

Figure 2 shows various foundation concepts. Extending the pylons and driving them directly into the ground is attractive due to the extremely low material costs and because no additional parts are needed. However, the investment costs for the installation machines are expected to be high. Since the higher investment costs are projected to be relativized with expected increasing quantities, the pile foundation concept will have a long-term cost advantage.

Figure 2. *Heliostat foundation concepts*

The extended part of the pylons is driven into the ground as a pile, which is referred to as a pile driving. Standards for this type of foundation from the construction industry are not directly applicable. This is because of differences in the dimensions of the pylons, the depth of the pile foundation, and the applied loads. Nevertheless, it is estimated whether the pylons as piles can basically transfer the required loads. Since the soil conditions are of fundamental importance for this estimation but are not available, a worst-case estimation is done. For this, the minima of the empirical values for soil strength given in the standard publication [5] are used. For soils containing a high percentage of rocks, pile driving is not a viable option and an alternative foundation must be selected.

2.2 Pylon loads

The wind load acting on the heliostat is the dominant load, along with the dead weight of the structure. Correlations derived from wind tunnel and full-scale tests as well as simulations are available in the literature to estimate the maximum loads as a function of various geometric parameters. For this work, the loads were determined according to [6].

The load-bearing capacity of a pile is divided into the axial and the horizontal load-bearing capacity. The maximum axial load is composed of the skin resistance and the pile toe resistance (Figure 3, left). The skin resistance results from the outer surface and the skin friction [7]. The pile toe resistance is not used here to calculate the load-bearing capacity due to the hollow cross-section. In reality, a plug of soil often forms in the pipe, which contributes to the load-bearing capacity of the pile. However, this is not assumed in the worst-case estimation. The horizontal load-bearing capacity is normally determined using the subgrade reaction modulus method and requires precise knowledge of the soil. In order to nevertheless carry out a worst-case estimate based on empirical values, the horizontal load-bearing capacity is calculated according to [7] with simplified assumptions (Figure 3, right).

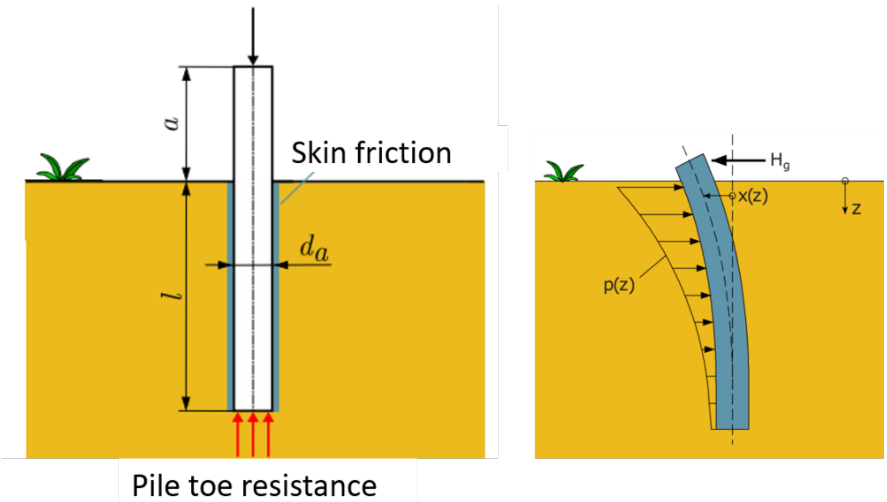

Figure 3. *Vertical load (left) and horizontal load (right)*

2.3 Vibratory driving

The pylon under consideration corresponds to a driven steel pile with a circular cross-section. This pile type can be installed with conventional impact hammers or vibratory pile drivers. In principle, it can also be pressed into the ground. Screw piles also exist. However, since these have a thread, the unit costs of the heliostat would increase too much. Sketches of these methods are given by Figure 4.

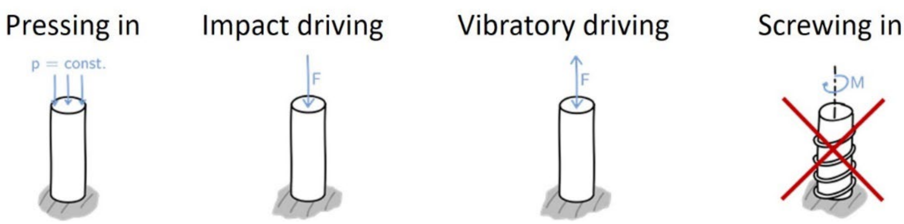

Figure 4. *Pile driving methods*

In order to safely drive the very thin-walled pylons into the ground without damaging them, it is essential that the soil resistance forces are as low as possible. This is the case with vibratory pile driving because the vibration of the pile causes the soil to vibrate which at the right frequency causes it to reach a pseudo-liquid state [8] [9]. This leads to a significant reduction in skin friction and consequently in soil resistance. [10] In addition to the effect of reducing skin friction, the formation of a plug should not be underestimated. In this process, the soil inside the pipe is tensioned due to the friction on the inside of the pipe and forms a plug. This plug acts like a pile foot and causes a pile tip pressure. This increases the load-bearing capacity of the pile, but also the soil resistance that has to be overcome. Due to the reduced skin friction (also on the inside) during vibratory pile driving, no plug formation occurs with these types of insertion [11]. The pile-driving forces are therefore lowest with vibratory pile driving. Further advantages are a larger pile-driving advance, i.e. shorter cycle times, and universal applicability in a wide range of soil conditions.

The required pile-driving force, estimated for soil with a high load-bearing capacity, is less than 100 kN and is in the range of lightweight vibratory pile drivers. The weight of such models is around 1000 kg. Vehicles for such pile drivers are correspondingly compact which saves costs.

3. Fastening of the concentrator with tracking device to the pylon

In a second step, after anchoring the pylon, the concentrator with tracking device must be positioned and connected to the pylon efficiently (Figure 5, left). The accessibility of the pylon only from outside means that many processes such as spot welding or clinching are not readily applicable. A fast and backlash-free joining solution with a target service life of 30 years is needed.

The most suitable joining method was found to be thin sheet metal screws. The advantages of the process are that such screws can be used without pre-drilling and the process requirements are low, as well as the possibility of using screwdriving machines handled by lightweight robots (Figure 5, right). Another advantage is the good market availability of these components.

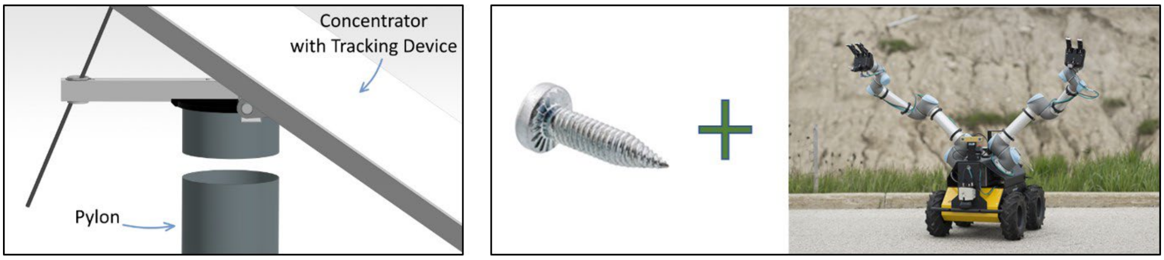

Figure 5. *Components to be joined (left), vehicle with screwdriving robots (right)*

4. Vehicles and route strategy

Once the two key process steps have been identified, the overall process and material flow has to be defined. Small outdoor Automated Guided Vehicles (AGV) (also known as unmanned ground vehicles, UGV) or comparably large autonomous lorries offer different options for handling the process. They have to carry the pile driving and joining machines as mobile manipulators and have to transport the pylons and the trackers with concentrators into the field. The resulting material flow must be coordinated reliably and efficiently. While a truck can transport more material at once, many smaller AGVs can realise a kind of substitute for a continuous conveyor. Modularity and redundancy can influence the costs and choice of the vehicle type. In addition, the installation route strategy is important to minimise distances, reduce waiting times and cycle times per heliostat, and thus reduce costs.

4.1 Heliostat field

Figure 6, left shows a solar field with 2,823 heliostats of a solar tower plant designed with the raytracing tool HFLCAL [12]. It is used as an example to develop an installation strategy. The distances between the heliostats mean that vehicles with a width of 1.8 m or more cannot drive between the driven pylons in the front rows. But the distance is also small in the rear rows. At the latest when the concentrator is installed, vehicles cannot drive between the heliostats that have already been installed. This means that the heliostats have to be installed in rows. Furthermore, components must be efficiently distributed in the field. The shortest routes are achieved when the rows are constructed from rear to front, i.e. towards the tower with the material storage located there. In this case, it is possible to drive in a direct line, thus saving operating time and energy costs (Figure 6, right).

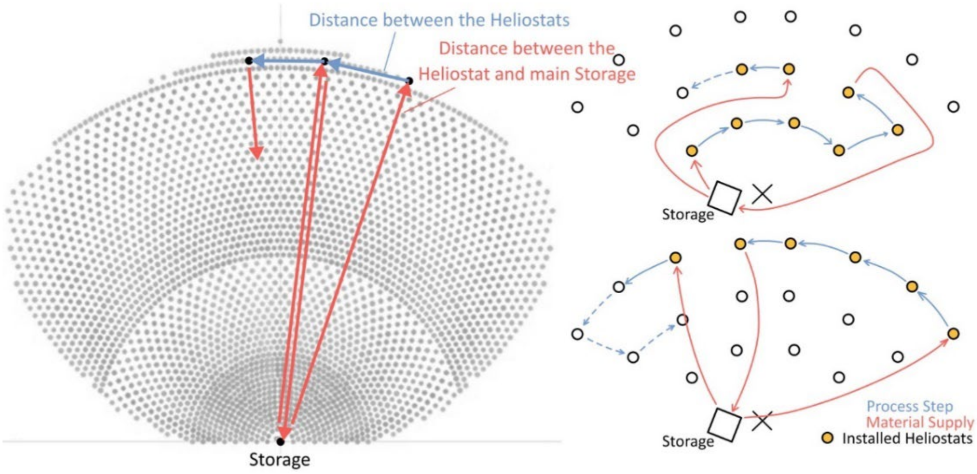

Figure 6. *Distances within sample heliostat field for driving time calculations (left), front to rear (right, top) and rear to front installation (right, bottom)*

4.2 Vehicles for machines and material

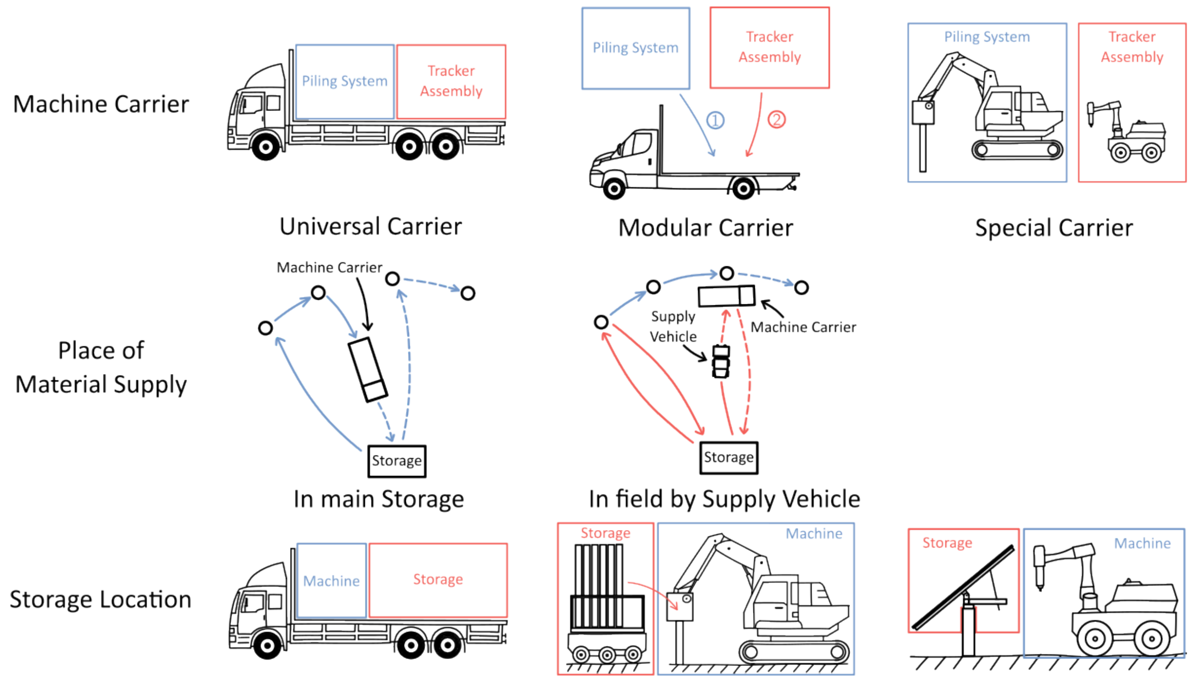

Figure 7. *Possible configurations for machine and material transport*

The machines for pile driving and joining must be transported in the field. The basic design rules of logistics must be applied to ensure an efficient installation process. The right material must be in the right place, at the right time, and in the right quantity. Various configurations of means of transport and machines are conceivable for this. The fundamental questions are: How are the machines transported? Are there one, several, or modular vehicles for the various process steps? How will the material supply be realized and where/how will the components be stored? Possible configurations are shown in Figure 7.

General material flow concepts can be derived from these options which are shown as routes in Figure 8. The blue arrows indicate the route of the vehicles which carry a machine (for pile driving or for concentrator and tracker fastening respectively), The red arrows show the routes of vehicles which carry material (piles or concentrator with tracker). The small circles indicate the positions of the piles to be driven into the ground or the pylons to which the concentrators with trackers have to be fastened, respectively. Each concept offers advantages and disadvantages that are difficult to evaluate in terms of cost optimisation.

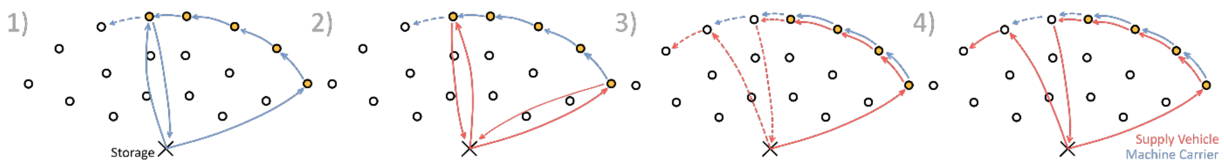

Figure 8. *Material flow concepts*

In concept 1) the machine carrier (blue arrows) also carries the material so no additional vehicle for material supply is required. However, the process step pauses while the vehicle returns to the main storage area to be reloaded. As a consequence, the utilisation of the machine carrier decreases.

In concept 2), the utilisation of the machine carrier is higher because the machine carrier does not return to the main storage location, but is supplied by a supply vehicle (red arrows). However, this increases the investment and operating costs. Since the components in concept 2) are still loaded onto the machine carrier, there is still a short break in operation during loading. The duration of this break depends on the design and capacity of the storage system on the machine carrier.

In concept 3), no storage system on the machine carrier is needed, but instead the supply vehicle follows the machine as a mobile storage system. Depending on the design, the reloading times are no longer than they would be with a storage system directly on the machine carrier. This way, a robot can, for example, cantilever over the machine carrier and take material from the mobile storage. However, the disadvantage is that the supply vehicle cannot return to be reloaded until all the material has been used up. To prevent waiting times during operation, at least two vehicles are therefore necessary.

Concept 4) decouples the machine carrier from the supply vehicle. Both vehicles operate independently, which means that there are no delays in the process as long as the supply vehicle deposits material faster than the machine processes it. However, this requires the creation of possibilities for safely storing the material in the field.

4.3 Cost assumptions

In order to evaluate which concept with which vehicles is most cost-efficient, particularly with regard to size and loading capacity, various configurations are calculated with the aim of estimating the costs per heliostat. To do this, the individual distances and the corresponding travel times of the vehicles are calculated. The distances depend on the loading capacity of the components and the chosen concept. The driving times depend on the acceleration and speed of the vehicles. In addition to the driving times, further times arise in the process:

- Cycle time: Time required to carry out a process step of the heliostat installation.
- Loading time: Time required to load a vehicle with components from the storage area.
- Transfer time: Time required to load components from one vehicle to another.
- Waiting time: Waiting times occur, for example, when the pile driving machine has used up all the material and has not yet received new pylons from the supply vehicle.
- Charging time: The time calculated for electric vehicles when the range/running time is reached and the battery needs to be charged.

Together with the driving time, this results in a total time for setting up a solar field. By defining an amortisation period for the machinery of the selected installation technology, the number of heliostats that could be installed in that period can be determined using the calculated construction time per heliostat field. The investment and operating costs divided by the total number of heliostats yield the installation costs per heliostat.

4.4 Results for sample case

The operating cost for the installation of a solar field are calculated from the energy costs and wage costs. The energy costs are based on the energy consumption for the kilometres driven by the vehicles. It is assumed that diesel costs €1.50 per litre and electricity costs €0.30 per kWh (as of 2024). In some concepts, the labour costs arise from the driving times of the supply vehicle if it is not autonomous, e.g. a conventional forklift truck. The hourly wage is estimated at €15, assuming that the country is a low-wage country. Since the input data for the calculation are only rough estimates, it cannot be assumed that the calculated costs (Figure 9) accurately reflect reality. However, a trend can be seen that indicates which concept should be used for which process step for the assumption that the machinery will be continuously used to install heliostats fields over a period of 10 years, 200 days each year, 10 hours a day. Shipping and set-up costs of the equipment depend on the locations and is not included but should be similar for all solutions.

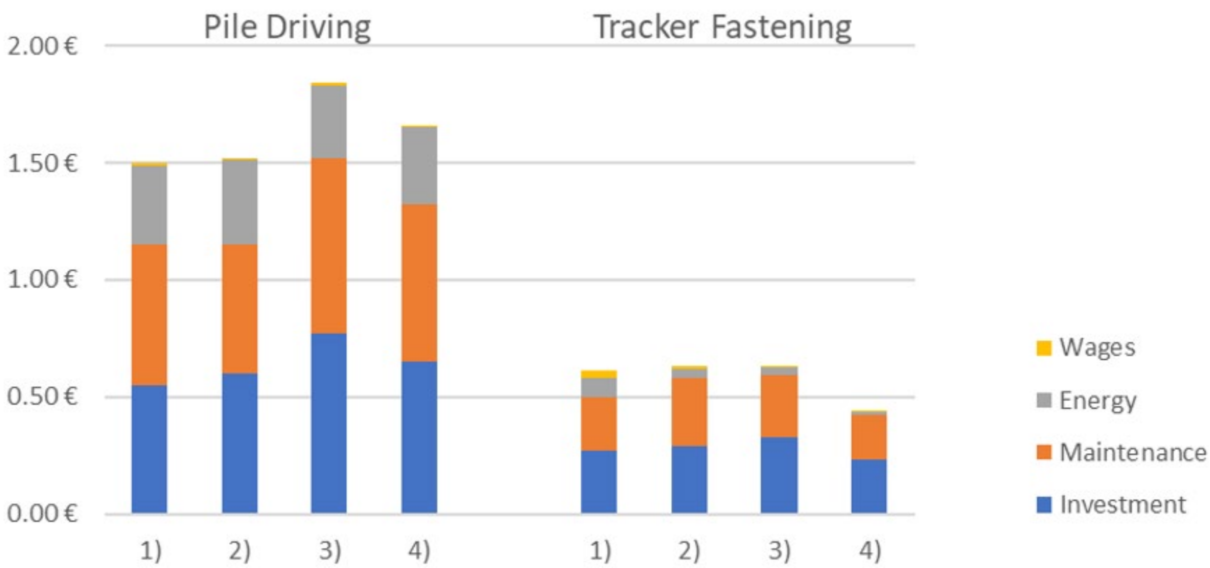

Figure 9. *Pile driving costs (left) and tracker fastening costs (right) for four material flow concepts*

The aim of this study is to present a method to compare possible installation concepts and not to give the generally optimum solution for heliostat installation. This is not possible since the optimum is highly dependent on the specific boundary conditions, especially on the number of fields to be installed. However, based on the given assumptions, the following combination was selected.

1. Pylon driving

- Process: Pile driving with light vibratory hammer
- Material flow concept: Concept 1) – Vehicle is loaded at main storage, no supply vehicle
- Machine carrier: Hydraulic excavator (8-18 t), small truck (7.5 -12 t) or special-purpose vehicle on a caterpillar track of a similar size – Loading capacity: min. 200 pylons (Figure 10)
- Sensors: RTK-dGNSS for determining the position, optional laser scanner for personal protection and to increase accuracy

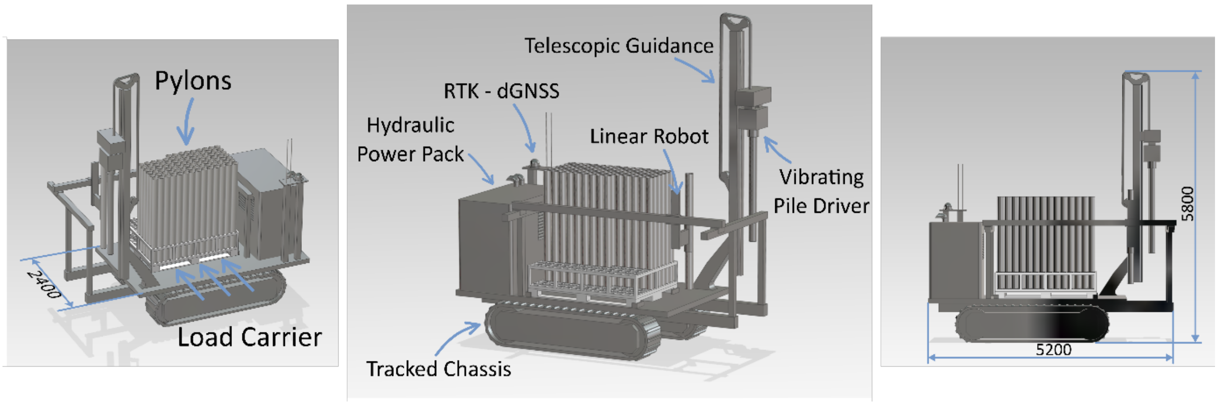

Figure 10. *Machine and material carrier for pile driving*

2. Joining of concentrator with tracking device to pylon

- Process: Joining with screwdriver on lightweight robot for screwing in thin sheet metal screws
- Material flow concept: Concept 4) – vehicle assembly supported by a supply vehicle that places the concentrator on the pylons with tracking
- Machine carrier: Small AGV (Figure 5, right)
- Supply vehicle: Medium-sized AGV – loading capacity 6 to 8 heliostats (Figure 11)
- Sensors: dGNSS for approximate positioning with LiDAR for 3D mapping and navigation using landmarks (pylons driven into the ground) as well as detection of the pylons for depositing/joining

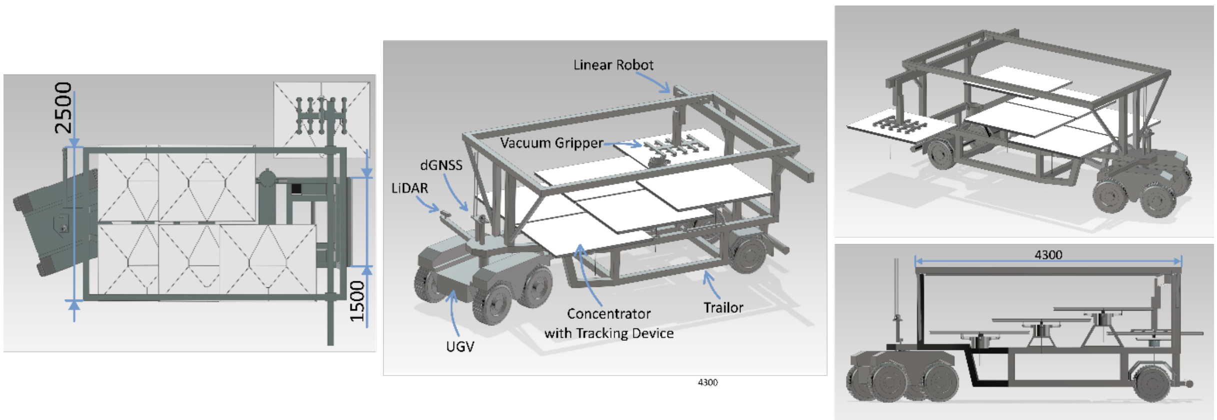

Figure 11. *Vehicle to place concentrator with tracking device on pylon*

5. Summary and outlook

In order to develop a concept for the automated installation of heliostats, various types of heliostat foundations were discussed. The direct driving of the heliostat pylons into the ground as a pile foundation has proven to be the most cost-effective solution. In order to assess the feasibility, the wind loads for the DLR heliostat design were calculated and the stability of the pile foundation was verified with regard to its load-bearing capacity in poor soil conditions. Based on a literature research into the state of the art of pile foundations and the calculation of the soil resistance forces for inserting the pylons, vibratory pile driving was selected This ensures the lowest possible component loads so that the very thin-walled pylons can be driven into the ground without damage.

The second process step involves transporting the concentrator with the tracking unit to the pylon and connecting them to the pylon. In view of the costs, the one-sided accessibility from outside the pylon, and the necessary machines, thin sheet metal screws were determined to be the most cost-efficient joining process.

Subsequently, various material flow concepts were developed to efficiently install the large number of components for an exemplary solar field with 2823 heliostats. The most cost-effective configuration was determined out of various carrier devices and material flow concepts, taking into account investment and operating costs as a function of the driven distances.

Finally, two design proposals for vehicles for process steps 1 and 2 were presented in detail. For process step 1, this is a heavy tracked vehicle with a vibrating pile driver and a stockpile of up to 200 pylons, which installs the pylons in the solar field and independently picks up supplies from the main storage area. Process step 2 is carried out by two vehicles, whereby a medium-sized autonomous vehicle places approximately 6 concentrators with tracking unit directly onto the pylons before autonomously retrieving supplies. A second small autonomous vehicle screws these onto the pylons. Figure 12 shows an illustration of the installation process of the solar field. Further details are given in [13].

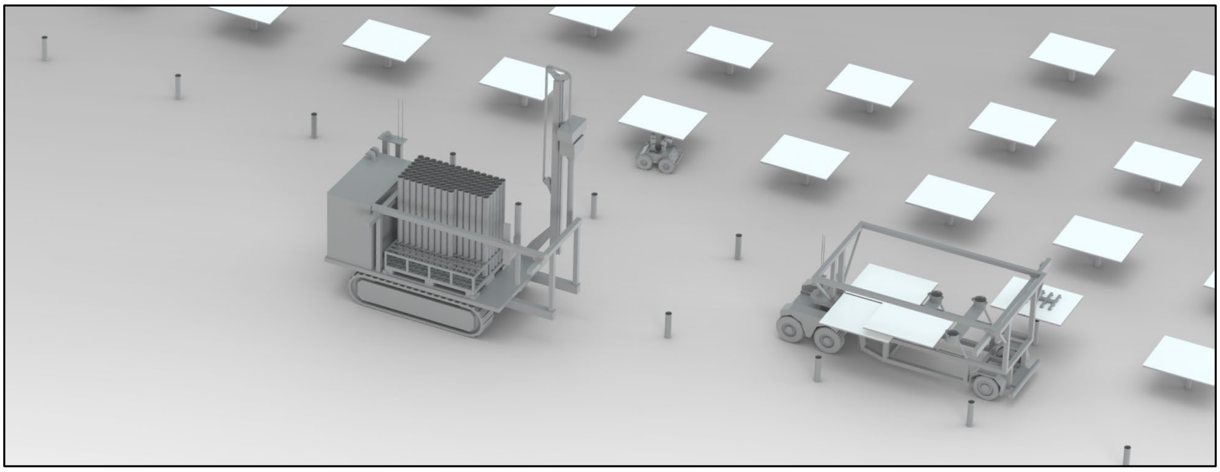

Figure 12. *Illustration of the installation process of a solar field: pile-driving vehicle (left), screw-driving robot (centre), placing vehicle (right)*

Data availability statement

All relevant data is given in the text or the referenced literature.

Underlying and related material

All important underlying and related material is given in the text or the referenced literature.

Author contributions

Lars Grobelny: Data curation, formal analysis, investigation, methodology, visualization, writing – original draft.

Andreas Pfahl: Conceptualization, methodology, supervision, writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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