Chapter 1

Introduction

1.1 Motivation

Scarcity of fossil resources, energy security, and climate change are forcing communities, states, and companies worldwide to pursue alternatives to the conventional power generation. At the latest with the Paris Agreement of the UN Climate Conference (COP21) in 2015, limiting global warming and mitigating climate change has become internationally aware and compulsory. To meet the current EU and national targets, renewable energy resources—mainly solar, wind, biomass, hydro, and geothermal energy—will play an important role in the world's future energy mix. However, technologies like Photovoltaic (PV) or wind energy are subject to strong fluctuations due to weather and daytime. As they additionally have a low energy storage potential, they are currently not suited to provide base load power. One key benefit of Concentrating Solar Power (CSP) represents its dispatchability due to large storage capacities of thermal energy in comparison to electric energy. Thereby, CSP is able to provide energy at clouded time periods or at night. [Teske and Leung, 2016]

The CSP technology is based on the principle of focusing incoming solar radiation on a specific absorber. Figure 1.1 shows the different technologies currently available. A distinction is made between point-focusing and line-focusing systems: solar towers as well as parabolic dish systems concentrate the available solar radiation onto a focal point, whereas Parabolic Trough Collectors (PTCs) or Linear Fresnel Collectors (LFCs) focus the sun light onto a receiver tube in form of a focal line. Depending on the implementation and type of construction, the systems may provide different levels of working temperatures. According to the temperature level and other characteristics, different heat transfer media are used: pressurized water, thermal oil, and currently molten salt are the commonly used fluids. Higher efficiencies may be reached with the direct evaporation of water—so-called Direct Steam Generation (DSG)—in the receiver, because the produced steam may directly be fed to the steam network or turbine and therefore no additional heat exchanger is required. [Lovegrove and Stein, 2012, pp. 3–7,17]

Concentrating collectors can be designed in two different scales. Large-scale collectors are implemented in larger solar fields for electricity generation, whereas small-scale collectors are used for industrial process heat integration. Apart from their scalability, also their modularity makes line-concentrating collectors particularly suited for the integration into industrial processes. By a flexible connection of the collector modules in parallel or series, the generated power or heat of the system may be easily adapted to the required

Figure 1.1: Overview of different CSP systems. Upper left: linear Fresnel collector (© DLR/Novatec), upper right: solar tower (© NARED/Abengoa), lower left: parabolic trough (© Schott AG), lower right: parabolic dish (© DLR).

demand. Heat generation in general represents 56 % of the final energy consumption in Germany. For industrial process heat, 21 % of the final energy consumption are required [Lauterbach et al., 2012]. Worldwide even 24 % of the final energy consumption are used for the heat generation in industrial processes [Horta et al., 2017]. For the reduction of CO_2 emissions, the energy statistics show the important role worldwide of renewable heat supply in general and small-scale CSP in particular, as these systems are able to provide the required working temperatures between 100–400 °C.

One important requirement for all CSP systems is a high direct solar irradiation over a long period of time within the year. Therefore, CSP facilities are only meaningful to be installed in sunny regions with semi-arid climate characterized by few clouds and clear sky. Figure 1.2 depicts the yearly sum of available direct solar irradiation worldwide. Regions marked in yellow show a high potential for CSP with a large offer of solar radiation—such as southern Spain, California, the Sahara region, Chile, South Africa, and Australia. Even though the CSP technology has expanded rapidly in the last ten years converting it from a newly introduced to a reliable energy generation solution, the installed capacity worldwide only amounts to around 4.9 GW (as of December 2015). Nevertheless, the potential of CSP is estimated far greater. In a moderate development scenario, the solar thermal power capacity is estimated to reach around 20 GW in 2020 [Teske and Leung, 2016].

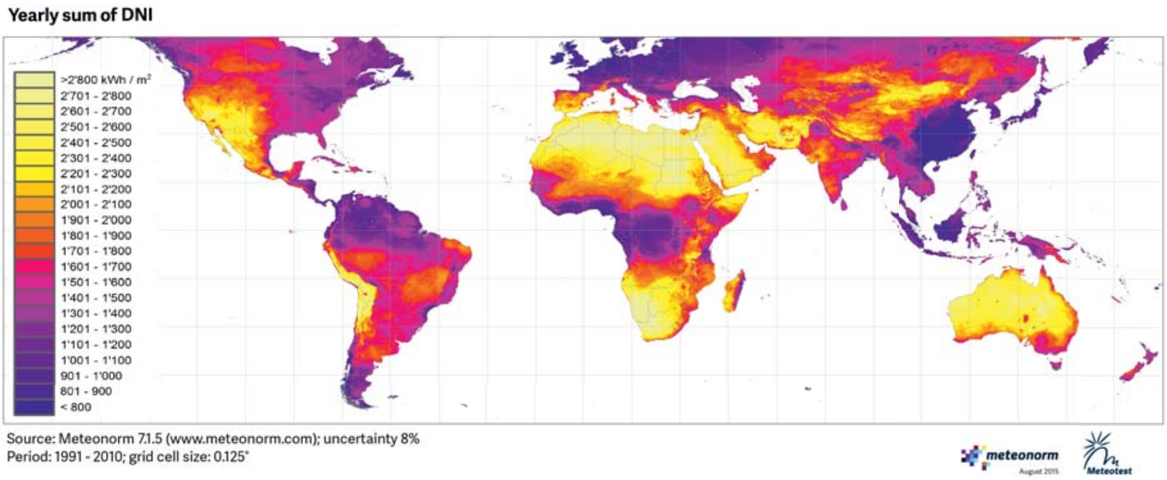

Figure 1.2: Worldwide available yearly sum of Direct Normal Irradiance. High potential regions are marked in yellow with DNI values > 2200 kWh/m^2 (© Meteonorm).

To fully exploit this potential, to establish and to increase the market penetration of this emerging technology, as well as to legitimize investments within this sector, a reliable and significant performance evaluation is essential. A dependable performance test sets the basis for a further development of the collector technology, as design and material improvements directly translate to increased efficiency or lower production costs. Moreover, reliable performance evaluation provides indicators for meaningful comparisons between collectors, which plays an important role for diverse aspects of standardization and certification. A quality label (such as the Solar Keymark [CEN and CENELEC, 2006]) creates transparency and comparability of the involved technologies, increases trust, and raises fair competition, resulting in a grown ambition to innovation.

Parabolic Trough Collectors (PTCs) as line-focusing systems currently represent the most common of the CSP technologies, being commercially installed since the early 1980s. Nevertheless, they still present a less established technology compared to low-temperature solar thermal collectors. Only since 2013, the currently valid and widely accepted testing standard ISO 9806 [ISO 9806, 2013, 2017] [1] also includes concentrating solar collectors within its scope of application. However, its content was not specifically adapted to concentrating technologies and therefore the testing standard is not fully applicable to concentrating collectors in general.

Concentrating collectors exceed the dimensions of standard low-temperature collectors by far. Accordingly, laboratory testing is hardly feasible for these types of collectors, requiring outdoor testing instead. In outdoor test facilities, steady-state measurement conditions as demanded in the indoor labs are very time consuming to fulfill, because ambient conditions like ambient temperature and solar irradiance cannot be controlled. Therefore, an alternative testing method based on a quasi-dynamic testing approach has been included in the testing standard ISO 9806:2013. It allows for dynamically varying

[1] Note that during the preparation until the submission of the present thesis, the international testing standard ISO 9806 in its version of 2013 was valid. Up to the final date of publication, a new version of the international standard ISO 9806:2017 was published—with its European EN and German DIN versions still pending. The work of the present thesis is therefore based on the testing standard ISO 9806:3013. Major parts of this version correspond to the updated version ISO 9806:2017 with slight adaptations and extensions, which do not significantly affect the general procedures referenced within the present thesis.

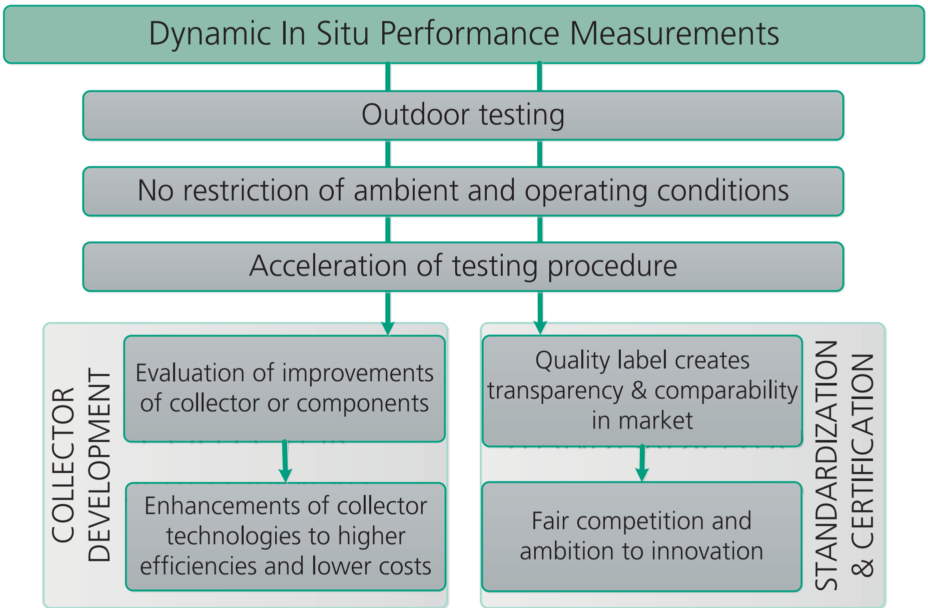

Figure 1.3: Aim and potential of dynamic in situ performance evaluation. The illustration focuses on development and standardization aspects of concentrating solar thermal collectors.

ambient conditions, but requires the inlet temperature and mass flow rate to be in steady state (yielding the naming of ‘quasi-dynamic’). Nonetheless, these outdoor measurements are very cost-expensive, since they require large heating and cooling capacities to fulfill the steady-state operating requirements. Moreover, concentrating solar collectors are preferably and more appropriately tested within larger systems (as they are installed for their actual purpose), in modules, collector loops, or complete solar fields. These facilities are mostly put up at the production site of the manufacturer or at the final installation site of the end user. On-site performance testing requires an adapted recording and evaluation of in situ measurement data, which mostly demands a more flexible evaluation of dynamic measurement data under unsteady ambient and operating conditions. Figure 1.3 summarizes the aim and potential of performance evaluations based on dynamic in situ measurements.

Against this background the need for a fully dynamic performance evaluation procedure for concentrating solar thermal collectors becomes evident. This thesis addresses this particular aspect of enhanced dynamic in situ performance testing of line-concentrating collectors. Among smaller features, the elaborated approach includes a quality assessment of the evaluation results, which is commonly not available for thermal collector testing so far. Besides, the thesis comprises a comprehensive guideline for the proper selection of measurement instrumentation as well as a detailed proposal of an appropriate testing strategy for line-concentrating collectors. Applying both aspects as recommended, the quality of evaluation results may be significantly increased. For the first time, the enhanced approach of this thesis additionally enables the dynamic evaluation of collectors operating with steam as a heat transfer fluid.

The basis of the methodology can be applied to point-focusing systems as well, but the below introduced performance evaluation procedure focuses on line-concentrating systems in general. As the recent technology of linear Fresnel collectors (LFCs) is less investigated than the one of parabolic troughs, several characteristics and particularities of LFC testing are specifically discussed within certain chapters of this thesis.

1.2 General Structure of This Thesis

To introduce the new performance evaluation method (referred to as the Dynamic Testing (DT) method within this thesis), the corresponding theoretical background is set in Chapter 2. As a basis for the specific enhancements required for the dynamic performance evaluation procedure, the state of the art and theory of dynamic collector testing with focus on concentrating solar thermal collectors is presented. Moreover, the chapter includes a summarized description of the used experimental facilities. The test facilities operating with solar collectors of different type, heat transfer fluid, and size provide a variety of measurement data for the validation of the proposed testing procedure. In this way, particular and individual elements of the procedure are validated on the one hand. On the other hand, the diversity of available measurement data ensures a comprehensive validation of the complete developed testing and evaluation procedure as a whole.

With the background set, Chapter 3 to Chapter 7 address diverse aspects and elements of the newly developed performance evaluation procedure. Detailed adaptations and enhancements of the dynamic testing method are derived, ranging from the general implementation structure, over direct steam generation, to the statistical assessment of the test results and including recommendations of appropriate measurement instrumentation as well as testing strategies. Note that the main theory of the general concept for dynamic performance testing is introduced in Chapter 2, whereas the specific methodology of the different elaborated elements are outlined within the corresponding chapters. This approach is pursued to assure a simple traceability of the structure, logic, and line of reasoning of the developed dynamic performance evaluation procedure.

The core of the proposed evaluation procedure is based on fitting measurement data of the test collector to simulation results, as schematically illustrated in Figure 1.4. Therefore, all developed elements of the enhanced dynamic testing method are related to specific parts of this fitting procedure. In Figure 1.4, the structure and sequence of the developed elements are sketched referring to the different chapters of the present thesis where the particular elements are discussed.

The general adaptation of the dynamic testing method concerning the specific evaluation structure, optimization procedure, and simulation model is derived in Chapter 3. The initial main premise for the further development of the dynamic testing method consisted in comparing and thereby validating it to the current state of the art in form of the normative Quasi-Dynamic Testing (QDT) method. As this method is not directly applicable for LFCs, an extension of it and its validation is introduced in Section 3.1.

One aspect of a comprehensive testing method lies in featuring a procedure applicable to collectors operating with different Heat Transfer Fluids (HTFs) such as pressurized water, thermal oil, and direct steam. Chapter 4 is dedicated to the adaptation of the evaluation method to DSG.

Dependable and meaningful reporting of test results requires specifications concerning confidence levels and uncertainty bands of the determined parameters. Therefore, one important element represents the statistical assessment of the evaluation quality. Its methodology and capabilities are described in Chapter 5.

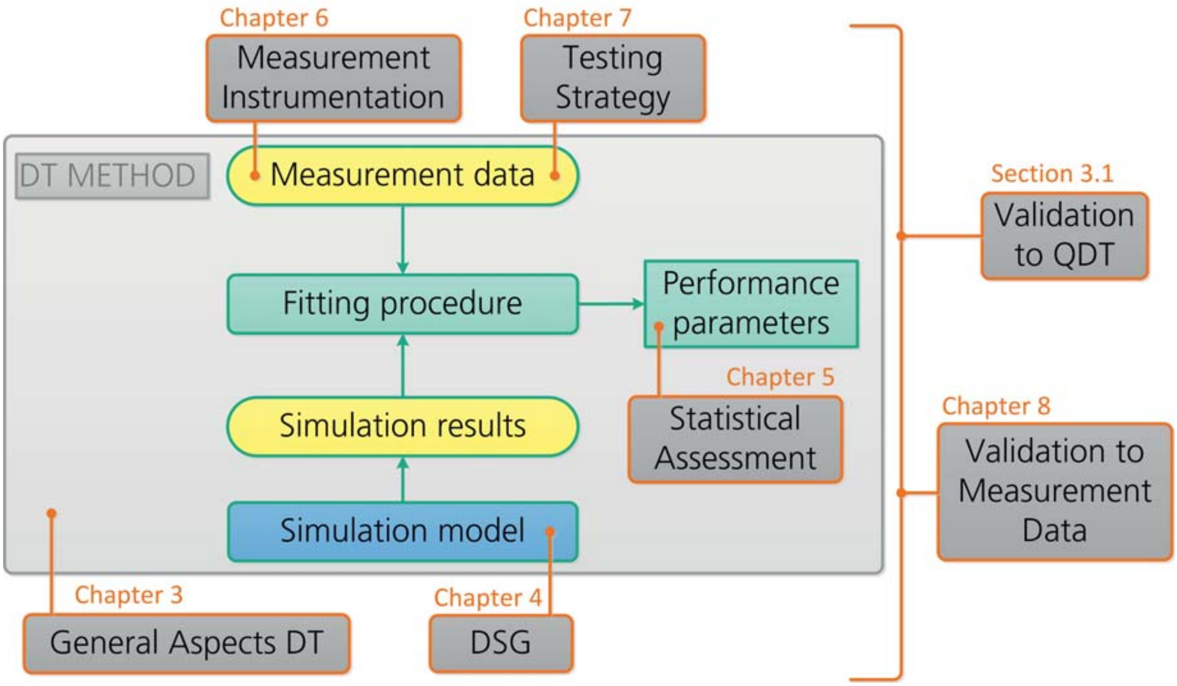

Figure 1.4: Investigated and developed elements of the dynamic performance evaluation method. Structure and sequence of the developed elements are sketched with respect to their relation to the DT method.

Measurement data constitute one key element of the testing method. To record significant and reliable measurement data, Chapter 6 comprises a guideline on the selection of proper measurement instrumentation depending on its uncertainties.

Moreover, the information content of the measurement data influences the quality of evaluation results and consequently determines the representativeness of the test results. For this reason, Chapter 7 presents the derivation and conclusion of a detailed testing strategy.

Finally, Chapter 8 includes the validation of the enhanced evaluation procedure to measurement data. It provides a comprehensive and general application of the newly advanced testing procedure to diverse test collectors ranging from small-scale medium-temperature linear Fresnel collectors to large-scale high-temperature parabolic troughs, including different heat transfer fluids and receiver designs. Thereby, the enhanced dynamic evaluation method is validated as a whole, proving its capabilities and practicability in terms of meaningful and reliable performance testing.

In the closing Chapter 9, overall results are summarized and concluded, allowing for the proposal of a comprehensive, consistent, and representative dynamic performance evaluation procedure.

Chapter 2

General Concept and Experimental Facilities

2.1 Literature Overview on Collector Testing Procedures

A detailed literature screening was compiled and already published in Hofer et al. [2016]. Wide parts of the following section correspond to this publication, with some paragraphs summarized, modified, or extended. The literature overview showed a multiplicity of different publications in the field of solar-thermal collector testing procedures. For this reason, the screened publications with their respective testing procedures were divided into two aspects: their testing methodology on the one hand and their application on the other, allowing a more structured and traceable comparison of the different testing methods. In Figure 2.1, the detailed literature review is summed up according to the introduced categories. The methodologies are grouped into Steady-State Testing (SST), Quasi-Dynamic Testing (QDT) and Dynamic Testing (DT), whereas the application of the published testing procedures is classified into non-tracking (stationary) collectors, tracking concentrating collectors, and large solar fields of tracking concentrating collectors.

The upper part of Figure 2.1, highlighted in light blue, shows that the majority of publications in the field of collector testing deals with non-tracking collectors. In this area, numerous testing and evaluation procedures have been published. For clarity reasons, publications of steady-state testing for non-tracking collectors have not been listed, as they are plenty and of less interest concerning testing procedures for concentrating collectors. Especially the quasi-dynamic testing procedure was investigated, adapted, and applied in several publications for different technologies, mainly based on the work done by the research group of Perers (e.g., see Perers [1993, 1997]). Moreover, the QDT method represents one of the proposed testing methods within the current testing standard ISO 9806 [2013]. As a counterpart to the QDT procedure, the dynamic testing method was firstly introduced by Muschaweck and Spirkl [1993], containing a more sophisticated collector simulation tool with the benefit of less restrictions in measurement data. The QDT method is based on a linear collector equation and quite strict boundary conditions, which allows the use of Multiple Linear Regression (MLR). In contrast, the DT method is based on different kinds of specific (dynamic) collector simulation models, allowing the evaluation of less restricted measurement data in terms of varying inlet temperatures, mass flow rates, and solar irradiance. Consequently, the use of dynamic

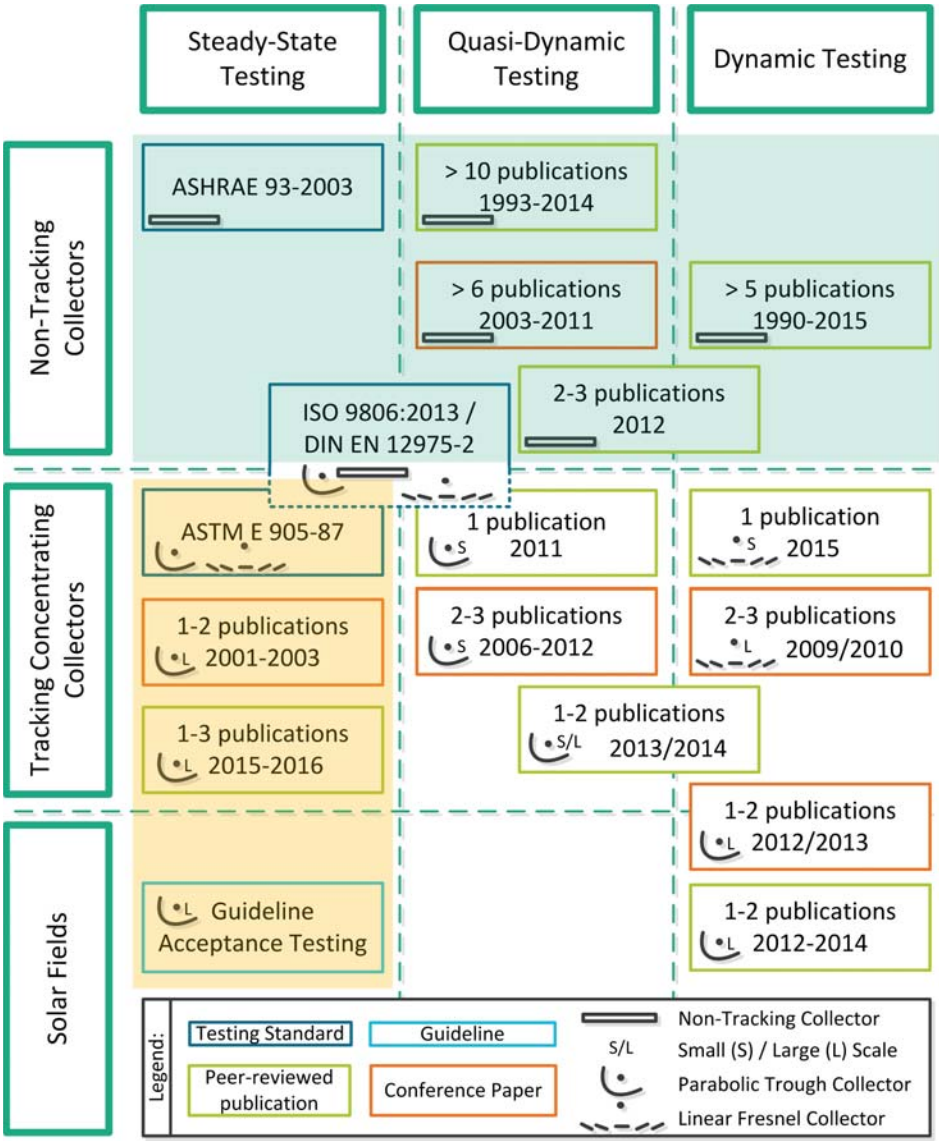

Figure 2.1: Summary of published testing and evaluation procedures with focus on concentrating solar collectors. Overview on state of the art of testing procedures in literature, differentiating between the type of testing method (steady-state, quasi-dynamic and dynamic) and its application (to non-tracking collectors, tracking concentrating collectors and solar fields). [adapted from Hofer et al., 2016]

models requires a combination with more complex optimization algorithms, consisting, for example, of a non-linear least-squares minimization approach or others. A comparison of both mathematical approaches by Fischer et al. [2003] showed that they are equivalent in their results, least-squares minimization only being more flexible in its application. An approach in-between QDT and DT is presented by Kong et al. [2012b]. It uses the MLR of the quasi-dynamic procedure with an enhanced linear collector equation, allowing for more dynamic measurements data. However, this approach is still reliant on some degree of steady-state data [see Kong et al., 2012a,b; Xu et al., 2012]. Additionally, numerous (quasi-) dynamic testing methods have been presented, differing in their specific physical, mathematical, or data collecting approaches. A detailed overview and comparison of (quasi-) dynamic testing methods in the field of non-tracking collectors can be found in Kong et al. [2012a] and Nayak and Amer [2000].

In the area of tracking concentrating collectors, the American testing standard ASTM E 905 – 87 [2007] is based on steady-state testing. Even a guideline for the acceptance testing of parabolic trough solar fields is based on steady-state measurements [Kearney, 2011]. Another approach of steady-state testing was applied for measuring the performance of large parabolic trough collectors [Valenzuela et al., 2014]. It is currently considered as a first reference approach for the proposal of a national standard in the Spanish National Committee AENOR[1] [see Sallaberry et al., 2016] and will be an input for discussion in the International Committee IEC TC[2] 117 (Solar thermal electric plants). Nevertheless, these testing procedures are either very time consuming or (if not the latter) mostly not comprehensively characterizing the collector or field performance, because they are limited to particular conditions (high solar irradiance, normal incidence at solar noon etc.).

In Figure 2.1, the testing standard ISO 9806:2013 is marked with dotted lines in the area of tracking concentrating collectors, as it is not fully applicable to all concentrating collectors without modifications. Publications in this field show that the QDT method is successfully applied particularly for small-scale parabolic trough collectors (marked with an S), because restrictions to measurement conditions can still be met [see Fischer et al., 2006; Janotte et al., 2009]. On this account, for a global characterization of large-scale collectors (marked with an L), either parabolic trough or linear Fresnel, mainly the dynamic testing method is applied, as with higher working temperatures, energy loads to be cooled to meet steady inlet conditions cannot be fulfilled easily. In particular, for the characterization of linear Fresnel collectors due to their special optical characteristics in terms of a two-dimensional Incidence Angle Modifier (IAM), new approaches by dynamic parameter identification [Platzer et al., 2009; Hofer et al., 2015a] or modifications to the QDT methods are inevitable (compare with Hofer et al. [2015a] and Section 3.1). This approach is pursued and developed within the present thesis. Xu et al. [2013, 2014] enhanced the QDT method for parabolic trough collectors, based on the work of Kong et al. [2012b], to be able to evaluate dynamic measurement data for these larger systems. However, the determined parameters of this new method do not correspond to any physical meaning, precluding a specific characterization of optical and thermal collector performance. This implies that the different identified parameters do not have a meaning on their own. Consequently, this approach is rather useful to evaluate the general energy output and system efficiency over a wider time span instead of balancing instantaneous collector power outputs.

Apart from the steady-state guideline for the acceptance testing of solar fields, there are few publications presenting a more sophisticated characterization and acceptance testing of parabolic trough solar fields based on dynamic testing procedures [see Janotte, 2012; Janotte et al., 2012, 2014]. Quasi-dynamic testing is rarely applied to large collectors or solar fields, which might be an indication that the QDT method with its restriction in measurement data is not entirely suited for the performance evaluation of larger systems.

With the existence of testing standards for non-tracking collectors (in Figure 2.1 highlighted area in light blue) and for steady-state testing procedures (in Figure 2.1 high-

[1]Asociación Española de Normalización y Certificación
[2]International Electrotechnical Commission Technical Committee

Table 2.1: Survey results concerning different currently used evaluation procedures and their specific application. The survey differentiates between testing method, collector and system under test, and heat transfer fluid used. [adapted from Hofer et al., 2016]

Category	Type	Share
Testing method	SST	8 %
	QDT	67 %
	DT	25 %
Evaluated collector type	parabolic trough	83 %
	linear Fresnel	25 %
	non-tracking collectors	33 %
System under test	solar collector	83 %
	solar field	33 %
Heat transfer fluid used	thermal oil	67 %
	pressurized water	50 %
	molten salt	8 %
	direct steam (SST)	16 %
	direct steam (DT)	0 %

lighted area in light orange), standardization in the area of dynamic testing procedures for tracking concentrating solar collector and fields is still lacking, while research and its publication is existing but scarce. To get a more comprehensive overview on current testing approaches, a survey on (not necessarily published) currently implemented dynamic testing and evaluation procedures was conducted within the European project STAGE-STE[3] (for more information see Hofer et al. [2016]). According to the list of participants, the survey was particularly concentrated on research institutions and relevant industries focused on tracking/concentrating solar thermal collectors and fields, as the literature review showed a gap of publications in this area (see right bottom part of Figure 2.1). Within the ten participants, the characteristics of 12 different testing/evaluation procedures were analyzed. Table 2.1 summarizes the general aspects of the different evaluation procedures.

The results show that around 67 % of the evaluation procedures are based on a quasi-dynamic testing approach. 25 % are based on dynamic testing procedures and 8 % are only able to evaluate in steady-state measurement conditions. They furthermore show that the majority (83 %) of the evaluation procedures are used for the characterization of parabolic trough collectors, whereas only 25 % are used for linear Fresnel collectors and 33 % for non-tracking medium temperature collectors[4]. 83 % of the evaluation methods are designed for solar collector evaluation, only 25 % can be applied to solar fields. Concerning the used heat transfer fluid for the characterization of the systems, mainly thermal oil (67 %) and pressurized water (50 %) are used, whereas only 8 % of the evaluation methods are performed with molten salt. A performance evaluation with direct steam based on a dynamic measurement approach does currently not exist within the partners of the survey. 16 % indicate that performance evaluation based on steady-state measurements can be performed. The figures show that the most commonly used evaluation method is designed for parabolic trough collectors operating with thermal oil or pressurized water. A reason why the evaluation methods can rarely be applied to other

[3]Scientific and Technological Alliance for Guaranteeing the European excellence in concentrating Solar Themal Energy

[4]The percentages do not add up to 100 % as there are several methods that can be used for several collector types.