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Review

Advances in Process Modelling and Simulation of Parabolic Trough Power Plants: A Review

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Abstract: The common design of thermal power plants is fundamentally oriented towards achieving a high-process performance, with market demands necessitating enhanced operational stability as a result of ongoing global support for renewable energy sources. Indeed, dynamic simulation represents one useful and cost-effective choice for optimizing the flexibility of parabolic trough power plants (PTPP) in a range of transient operating conditions, such as weather changes, resulting again in variations of the output load as well as varying start-up times. The purpose of this review is to provide an overview of steady-state and dynamic modelling for PTPP design, development, and optimization. This gives us a greater opportunity for a broad understanding of the PTPPs subjected to a variety of irradiance solar constraints. The most important features of the steady-state and their uses are reviewed, and the most important programs used in steady-state modelling are also highlighted. In addition, the start-up process of the plant, thermal storage system capacities and response dynamics (charging and discharging modes), and yearly electricity yield can be analyzed using dynamic modelling. Depending on the dynamic simulation, specific uses can be realized, including control loop optimization, load estimation for critical in-service equipment, and emergency safety assessment of power plants in the event of an outage. Based on this review, a detailed overview of the dynamic simulation of PTPP, and its development and application in various simulation programs, is presented. Here, a survey of computational dynamic modelling software commonly applied for commercial and academic applications is performed, accompanied by various sample models of simulation programs such as APROS, DYNAMICS, DYMOLA, and ASPEN PLUS. The simulation programs generally depend on the conservation equations of mass, momentum, species, and energy. However, for the equation of equilibrium, specific mathematical expressions rely on the basic flow model. The essential flow models involved, together with the basic assumptions, are presented, and are supplemented through a general survey covering popular simulation programs. Various previous research on the dynamic simulation of the PTPP are reviewed and analyzed in this paper. Here, several studies in the literature regarding the dynamic simulation of the PTPP are addressed and analyzed. Specific consideration is given to the studies including model verification, in order to explore the effect of modelling assumptions regarding the simulation outputs.

Keywords: parabolic trough power plant; dynamic simulation; flow models; load variations

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1. Introduction

As a result of the global environment's limitations in the supply of fossil hydrocarbons, coupled with the negative impact of CO_2 emissions, the growing use of renewable energy options is becoming imperative. Solar energy (SE) has a significant contribution to renewables, helping to meet the energy requirements of countries where sunlight is abundant. SE represents a renewable natural resource, which is inexhaustible and available on a local basis. Two major ways of making profit from solar energy are photovoltaic technology and concentrating solar power technologies (CSP) [1].

There are three layers in a PV cell, which are built up by joining semiconductors into thin flat sandwiches. The produced electrons are forced to pass across the central layer (junction layer). As a result, an electric current is generated, and a voltage is built up. CSP technologies generally depend on the concept of concentrating solar irradiation incidents on mirrors for generating either steam and/or hot air, all of which may be utilized in conventional power cycles for electricity generation. CSP is considered one of the main technologies in the production of electrical energy, and what distinguishes it from PV is the possibility of producing electricity at high capacities, as well as storing excess solar energy in molten salt or other fluids [2].

These CSP technologies are categorized into four primary technologies, namely, parabolic trough (PT), linear Fresnel, central tower, and parabolic dish. The PTPP remains widely used in solar power plants worldwide, as depicted in Figure 1, especially in Spain and the U.S., where the current capacity of operating plants is more than 2370 MW and 1836 MW, respectively. Power plants range in capacity from 5 to 280 MW [3]. The research deals with various solar technologies, and the most prominent among these technologies is the PTPP. This study is important in identifying the most important problems and solutions for this type of plant. In addition, this type of plant is the most widespread in the world compared to the other technologies because it depends on steam generation, and, therefore, can be used in steam turbines to produce large quantities of energy.

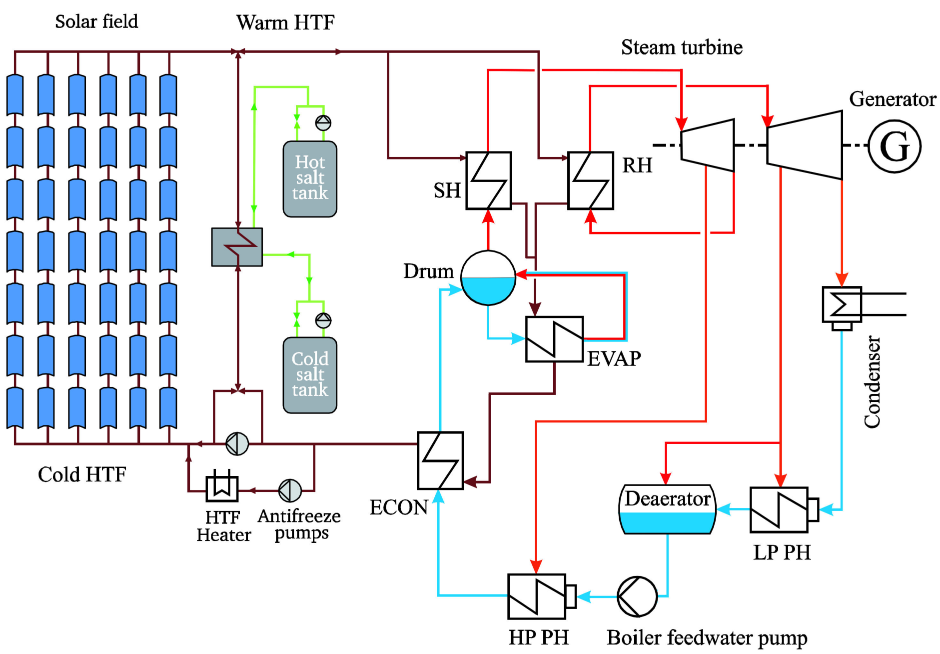

Figure 1. Parabolic trough power plant with a thermal storage system.

The working principle of PTPP depends on either generating steam directly in the solar field and then transferring it to the power block, or heating the thermal oil or molten salt and sending it to the steam generator to produce steam. In both methods, the generated steam is transmitted to the steam turbine to produce mechanical work, then generate electricity, before being transferred to the national grid. The advantages and disadvantages of PTPP can be listed in Table 1.

Table 1. Advantages and disadvantages of parabolic trough power plant [4].

Parabolic Trough Power Plant	
Advantages	1. Working temperature up to 500 °C (400 °C proven commercially) 2. Configurability 3. Favorable land-use factor 4. Minimal material requirements 5. Successful hybrid approach 6. High storability
Disadvantages	Nowadays, using oil as HTF limits working temperatures to 400 °C, which results in only medium steam properties.

In general, the thermal power plant is usually operated under constant design loads; however, it also has to operate under off-design load requirements because of the oscillations of demand and supply in electrical power, and the integration of renewable energy resources. The operating flexibility of the PTPP is, therefore, a fundamental factor for dependable grid stability. These requirements are translated to new challenges for operations, classified into the following three groups:

- Larger variations in load are needed across positive and negative load gradients. In addition, start-up and shut-down dynamics responding to a steep load gradient in the power distribution system also need to be improved;
- The possible range of PTPP operation must be re-evaluated according to the technically required lower load. A complete shut-down is often not desirable, therefore, the number of start-up/shut-down processes and the lifetime consumption of thermally stressed parts can be reduced by decreasing the minimum load;
- The high efficiency of thermal power plants at part load is relevant, because their original operation was at nominal load almost all the time; therefore, they run in load-following operations. Hence, a thermo-economic improvement in various nominal loads and off-design load regimes is fundamental. The parabolic trough power plants that include these new levels of performance characteristics maintain a distinct competitive benefit in the commercial electric markets.

Dynamic modelling gives designers an effective method when it comes to enhancing power plant efficiency and control loops, and evaluating the plant's limitations and possibilities in terms of materials, processes, emission, or cost-effectiveness. Thus, high demands are placed on the model efficiency and the accuracy of the computational solution process. Many solution algorithms, tools, and component libraries are provided by modern simulation codes for modelling and simulating large-scale behavior of dynamics. These simulation programs depend on various thermal–hydraulic programs, based on three conservation equations for mass, momentum, and energy, as well as experiential relationships for heat transfer and friction. For the non-steady modelling of PTPP, various components, such as pipes, pumps, drums, and heat exchangers, etc., are needed. In addition, a PTPP consists of a number of controllers and some electrical elements. The precise determination of the control configurations and operating strategy becomes essential for obtaining a sensible dynamic regime. Knowledge of each electrical element is important in performing dynamic modelling, in order to calculate the consumption of electricity and to determine failures due to power outages.

This study has four main parts. Part one presents the mathematical approach to energy system modelling, including providing an outline of simulation programs used to estimate the system response at steady-state and dynamic simulation conditions. The second part of this work refers to several relevant studies in the literature that explain the application of steady-state and dynamic simulations for PTPP. Part three demonstrates the most important steady-state and dynamic software used in the modelling of PTPP. The fourth part introduces the solution method for different dimensional flows.

2. Background of Mathematical Modelling

New PTPPs need to be optimized to provide high effectiveness and adaptability during load changes, and start-up and shut-down processes. Complementing experimental efforts, mathematical modelling contributes to an improved understanding of the processes, their possibilities, and boundary conditions; therefore, they are considered an essential part in increasing power plant efficiency. In general, the selection and optimization of thermal power plants begins with the modelling of the steady-state. This assumes that the PTPP is constantly operated on its nominal load. There is no need for control loops in the steady-state model, which depends mathematically on mass, momentum, species, and energy balances. Steady-state simulation tools can be applied to mass and energy fluxes, analysis of thermodynamic characteristics of the working medium, and optimization of process efficiency to a range of operating points. However, transient operating conditions are not considered with steady-state simulation tools. Therefore, it is appropriate to conduct the analysis of the operation process during non-steady periods, load fluctuations, and disturbances by using dynamic models. The engineering dynamic simulation approach is a helpful tool when designing a power plant project, and when searching for the optimal operation approach. However, the study of PTPP dynamic response needs a deep description regarding thermal processes. In fact, the complexity of the differential conservation laws that govern the inherent numerical methods and their solutions leads to dynamic simulation codes, and require highly advanced computer programs with long development times. The thermal–hydraulic models depict the steady-state and dynamic approach of a one-phase or two-phase flow. In PTPP, a majority of the processes involve the production of superheated steam under high pressure to drive a steam turbine, coupling it to an electrical generator. Two-phase flows are commonly applied in water–steam evaporator cycles. Such a flow is complex and multifaceted; therefore, a series of two-stage models are presented throughout the relative publications, with different degrees of difficulty. Usually, two types of models exist for describing two-phase flow models: the first kind, the two-phase flow, can be regarded as a mixture and approached similar to a single-phase flow model with quite complex thermodynamic characteristics. Steam and water are considered in thermodynamic balance, with the same velocity, temperature, and pressure. The second kind considers each phase as a separate fluid in the two-phase flow models. Consequently, two groups of conservation expressions are presented for liquid and gas phases. Furthermore, sufficient constitutive and experimental equations should be provided. These can be used for transport and thermodynamic properties, or as correlations for heat transfer coefficients. According to the six equation model, the two-fluid model is a uni-pressure model. Hence, there is mechanical equilibrium between the two phases, but not thermal and chemical balance. The seven equation model treats the phases as completely independent of each other. In this type of flow model, the fluid dynamic interface problems and the two-phase flow system are solved simultaneously, leading to separate pressure, temperature, velocity, and chemical capabilities for the two phases. The five equation or four equation version of the two-fluid model is based on thermal and mechanical balance, but not on chemical balance [4].

The researcher in a previous publication used many methods to implement the two-phase flow of PTPP, for instance, the mixing flow model or two-fluid models, which include the four equation, five equation, six equation, and also the seven equation flow models. Two-fluid models use two groups of conservation laws that determine the mass, momentum, and energy balances associated with each phase. A considerable number of difficulties are associated with this approach, because of the mathematical complications and uncertainty involved in modelling the interaction of the phases at the interface between them. In general, such correlations are not derivable based on basic physical principles; instead, they often rely on experimental assumptions. Finding solutions to the resultant differential equations needs more calculation capacity, and involves variables leading to computational instability, particularly due to the unsuitable choice of interface parameters. The problems that occur using the two-fluid model are treated through the formulation of the two-phase flow in the form of the mixture flow model. In this case, there are three fluid characteristics calculated, including the total mass flux, local pressure, and temperature or enthalpy, expressed in terms of three conservation laws (mass, momentum, and energy) for the mixture. Hence, this model is important due to the reaction of the entire flow of the mixture, rather than that of the individual constituents, which is often adequate. On the other hand, the two-fluid model becomes more suitable for particular uses because it provides the possibility of including thermodynamic non-equilibrium cases in the expression. Moreover, the two-fluid model treats the conservation equations, and this leads to describing phase limitations in a simpler method. However, an obvious problem with the mixed flow model occurs when it utilizes many closure models, leading to inaccurate results for specific applications [5].

Nowadays, advanced simulation codes include a comprehensive graphical operator interface of flow, heat transfer, and thermodynamics models. These computations give a fast evaluation for the planning of new plants, plant optimization, changes in processes, plant safety and security, and operating behavior during malfunctions, as well as operating behavior in off-design loads, base loads, and start-up and shut-down processes.

These simulation codes' mathematical background depends on the equilibrium equations for mass, momentum, species, and energy. The complication of these relationships, and the necessary computational solution algorithms, are initially based on the type of flow (steady-state flow, quasi-steady flow, or dynamic flow); the differences between these types of flow are as follows:

1. In the steady-state case, there is no need to consider the time derivatives in the conservation laws;
2. In the quasi-steady case, certain parts of the temporal derivative have no relevance and can, therefore, be neglected by the conservation laws, and this leads to significantly simplifying the system of equations;
3. In the dynamic case, sufficient consideration must be given to the temporal derivatives.

Secondly, the complexity of conservation equations is also based on the flow dimension (zero-dimensional, one-dimensional, two-dimensional, or three-dimensional); the solution method of these flows are briefly explained below [5]:

1. Zero-dimensional modelling case: no local discretization is considered in this case. This modelling of PTPP parts, such as pipes, pumps, condensers, heat exchangers, turbines, etc., is implemented by a system of algebraic equations containing the input and output conditions of these parts (such as mass flow rate, pressure, enthalpy, and void fraction);
2. One-dimensional modelling case: the components of the PTPP in-between the inflow and the outflow are discretized in finite cells, referred to as a numerical mesh. Consequently, a system of algebraic equations is used to estimate the partial differential equations. Eventually, the case parameters, for example, pressure, temperature, and enthalpy, can be calculated at each discrete location;
3. Two- or three-dimensional modelling cases: it is necessary to discretize the extra points locally. This, in turn, leads to the calculation of PTPP components becoming more detailed and having a higher cost.

In many technical fields, the steady-state process parameters are adequate. The computations of designers at various levels of the load are also carried out using these types of steady-state simulation models. A dynamic simulation enables investigating the non-steady-state operating period for the whole PTPP in conjunction with its control loops. Despite the advantages that dynamic simulation provides, it must be borne in mind that the modelling effort and computational time are significantly higher compared with steady-state modelling.

A number of available codes and commercially available software programs are applicable for the steady-state and dynamic simulation of PTPP, e.g., IPSEpro, APROS, GATECYCLE, PROATES, KPRO, PEPSE, PMAX, PROSIM, Thermoflow (GT MASTER, GT

PRO, STEAM PRO, THERMOFLEX, etc.), VALI, ASPEN Plus DYNAMICS, and EBSILON Professional. These programs include some that provide specialized libraries of components needed both for the steady-state and the simulation of power systems over time, such as the simple cycle of PTPP, combined cycle, and a wide range of other plants. Still, the researcher can use other software, i.e., MATLAB/SIMULINK, to access an open interface for non-standard parts modelling. Complicated physical schemes with control circuits and mechanical elements are possible to model using the non-proprietary object-oriented (equation-based) language MODELICA. On the basis of MODELICA, several types of commercial and non-commercial modelling environments supporting simulation were recently introduced, e.g., DYMOLA, SimulationX, and JModelica.org.

The most important programs for dynamic simulation can be mentioned in Table 2, e.g., Advanced Process Simulation Software (APROS) [6–13], ASPEN Plus DYNAMICS [14,15], ASPEN HYSYS, RELAP [16], MATHEMATICA [17], DYMOLA (based on Modelica language) [18–22], SIMULINK [23], and TRNSYS [24]. These programs originated from improvements made over a long period of time by universities or companies, and, generally, are not freely available. Lists of these programs represent a limited set of well-known codes currently applied in scientific research and industrial applications.

Table 2. Simulation programs [5].

Investigation Type	Software	Comment
PTPP	APROS	APROS is considered one of the most comprehensive programs in modelling power plants in general, and, in particular, a PTPP. This program can accurately model the plants because it contains all the parts of the modelling, such as pipes, pumps, heat exchangers, and other parts of the power plants. In APROS, real external data can also be added, which is considered as an input to the plant, such as adding the DNI measured at the plant's site or using the solar data present in the APROS library, which is an average and not the real data measured on that day, but rather the measured data of that date over several years and their average. In addition, it can create advanced control circuits. Multi-day dynamic simulation can be carried out continuously. APROS is considered the best program for modelling various power stations, especially in dynamic machining, due to its high flowability in performance, as well as the accuracy and rapid response to sudden changes during load changes. Most of the previous research dealt with dynamic modelling and simulation of PTPP.
	TRNSYS	At present, the majority of dynamic research papers published in the relevant studies focus on PTPP, while a limited number of studies are related to the solar tower and linear Fresnel systems, and none of the research papers refer to parabolic trough systems.
	ASPEN HYSYS ASPEN PLUS DYNAMIC DYMOLA MATLAB SIMULINK	To date, most investigations concentrate on providing facility dynamics at the in-system level, taking into account unsteady solar irradiance, and other studies examine the dynamic response of sub-systems, such as thermal storage systems.

In the following sections, a summary of the steady-state and dynamic responses for a PTPP previously used to enhance and assess techniques to improve the plant's operational versatility is presented. These types of models for PTPP simulations help improve the process understanding, and the possibilities and limits associated with the operation of a PTPP.

3. Steady-State Simulation Models

Most research works carried out as part of this field involve the designing, modelling, and evaluating of sections of the system based on steady-state simulation models. The control circuits are not required in the steady-state models, and are mathematically simulated using mass, momentum, and energy conservation equations. Nevertheless, the non-steady-state operating environment may have an impact on the efficiency of the PTPP under study. A current search of the relevant literature indicates that many investigations in regard to the improvement of the PTPP use steady-state simulations.

Fernández-García et al. [25] designed a test loop called CAPSOL, which meets the requirements established in the standards, and was built to properly evaluate small PTC behavior in actual ambient conditions. The performance and adequacy of the test loop were verified throughout an extensive test session using the CAPSOL loop. Since no consensus was established, the above test session set was taken advantage of to obtain the information below, which can be used to determine the ideal experimental protocol: (1) The appropriate response time is 5 s, which is the midpoint of the allowable range of ASTM E905-87 and ISO 9806 standards. (2) The appropriate period (for collectors of the short duration of response, minimum) is 15 min during preconditioning and 10 min during testing (according to the EN 12975-2/ISO 9806 standards). Kearney et al. [26] explained the testing method and measurement devices for parabolic trough power plants, without any details on which model can be used in this analysis. Several thresholds were addressed, the most important of which is the length of the steady-state testing period and solar power performance system. Sallaberry et al. [27] proposed a testing methodology based on taking a large PTC in the Plataforma Solar de Almería. This methodology was validated according to a previous study [28], depending on steady-state conditions. Findings indicate that the suggested method for the on-site testing of parabolic trough collectors proves to be valuable and simple in implementation. Biencinto et al. [1] developed a direct steam generation (DSG) simulation model in a PTPP, using the TRNSYS software environment with the help of new components. This model depends on steady-state behavior while also dealing with an unsteady response such as shutdown, start-up, and cloudy periods within a suitable processing period. The updated quasi-dynamic model provides several characteristics, including fast computation with satisfactory accuracy, the ability to use various types of solar collectors, and consideration of thermal inertia during transient procedures. Furthermore, the model validation was achieved based on the comparison of the values of the DISS solar measurement circuit at Plataforma Solar de Almería, Spain with the simulated results for the pressure and temperature of HTF at the solar field (SF) inlet and outlet. Sallaberry et al. [29] introduced a new model and a sample of the verification carried out on a PTC installed inside Plataforma Solar de Almería (PSA). This study was performed on the basis of quasi-dynamic conditions, which justifies the feasibility of neglecting the wind-dependent impact. Nation et al. [30] presented an innovative receiver for electrical power storage for PTC. This receiver was mathematically solved based on numerically solving a quasi-transient model of 2 transient and 10 steady-state equations, due to the receiver's all-important nodal temperatures and heat flows. This model was also confirmed against measured values received by the National Renewable Energy Laboratory (NREL) using available Solel UVAC3 and SCHOTT PTR-70 absorber tubes. An equation for the heat flow transmitted across the wall, which is strongly non-linear, was obtained by combining the steady-state equations. The goal seek task, accessible in Microsoft Excel, was used for solving the non-linear equation. It can be observed that it gives good forecasts for the main operational characteristics. Salazar et al. [31] evaluated a detailed analytical performance modelling of PTPP. The heat transfer process was analyzed inside, and from the solar collectors during the transient and evening periods. Furthermore, the influence of the solar collector operation on power block efficiency was studied. Detailed analyses in this model were conducted according to steady-state conditions. Direct normal irradiation (DNI) data were provided only on an hourly time range (instead of, for instance, a one minute time range). The measured data published in the literature for parabolic trough power plants are limited. Therefore, these data were used to verify the model on an hourly and monthly basis. The comparison shows reasonable agreement. The analytical model was applied to assess a PTPP currently being designed in Brazil, and to highlight the advantages of power delivery at the sites close to the Equator. Murtuza et al. [32] modelled a parabolic trough collector using an ANSYS software environment. Experiments were conducted throughout the year. The average water supply and discharge temperatures were measured. Furthermore, experiments were achieved with several water flows (0.4, 0.8 and 1.2 L/min) on an annual scale. Thereafter, the simulation results were compared and analyzed to the measured data when subjected to statically loaded situations to confirm the effectiveness and ruggedness of this construction.

4. Dynamic Simulation Models

The use of dynamic models is necessary in order to better understand and analyze the main specifications of the operating system during weather and load changes. As opposed to steady-state flow designs, dynamic flow models demand the transient equation solution involving the three main conservation equations (mass, momentum, and energy) and control circuits. In addition, dynamic simulation becomes a powerful means for evaluating regulation approaches, potentialities, and boundaries. Actually, one can find various commercial tools used for PTPP modelling, namely EBSILON Professional, MATHEMATICA, EcoSimPro, DYMOLA, IPSEpro, GATECYCLE, TRNSYS, and APROS. The NREL provides the System Advisor Model (SAM), which is a free but closed-source package, and it depends on the TRNSYS simulation code, while, for instance, SOLERGY is considered a cost-free, open-source model. A comprehensive outline of programs usable for CSP systems is performed. Since PTPPs have the widest use, it provides the highest reliability operation database, and is often applied to verify the dynamic model. Very limited work on dynamic simulation of PTPP is available in the published literature. In this section, an in-depth review of dynamic modelling for PTPP is included.

Twomey et al. [18] developed a dynamic model of DSG for the PTC loop. Various feed water control loops were designed and assessed using the MODELICA language. The model was then validated using the measured data. Furthermore, they investigated different feed water control circuits. Henrion et al. [7] implemented a thermodynamic type model for estimating the required backup portion for a 100 MW_{el} hybrid solar–fossil–PTPP. The objective of this work was to predict the capacity and explore its utility for location choice within four sites. Janotte et al. [33] introduced a dynamic approach for a PTC to provide an assessment of the PTC throughout the ongoing variations associated with operational environments. This evaluation includes performance data, measurement properties, and uncertainties for characteristic performance parameters. Silva et al. [34] presented a non-linear dynamic three-dimensional model of a PTC under several irradiance regimes in Modelica. They combined it with a model of the heating process with the TRNSYS program. The dynamic improvement of SF outlet temperature and steady-state thermal performance in comparison with measured data are found to be in reasonable agreement, with a mean square error of 2.09 °C and 1.2%, respectively. Russo [16] used molten salt in a PTPP. This model was carried out using modified RELAP5 code. This power plant includes a water/oil steam generator and a direct storage system. The model was validated according to the measured data. Furthermore, thermal–hydraulic behavior, and filling and draining procedures were analyzed. Figure 2 shows the draining phase in the collector C; collector A is emptied within approximately 1250 s, while collectors B and C are emptied in less time (approx. 250 s). Figure 3 displays Vent valve mass flow rate and total mass flow in the circuit. Molten salts remain inside the pipe (according to the siphon) joining collectors B and C and the element just after the siphon (void fraction of 150,090,000), with a time delay of around 250 s to drain; compared to the initial setup, on the contrary, this second case represents a better solution for the drainage phase management, considered as a condition of criticality for the molten salts solidification. Ehrhart et al. [35] focused on the collector platform optical performance, which is dynamically simulated. The flotation characteristics for the current platform type were verified both experimentally and numerically, and the impact on the performance during operation offshore is low.

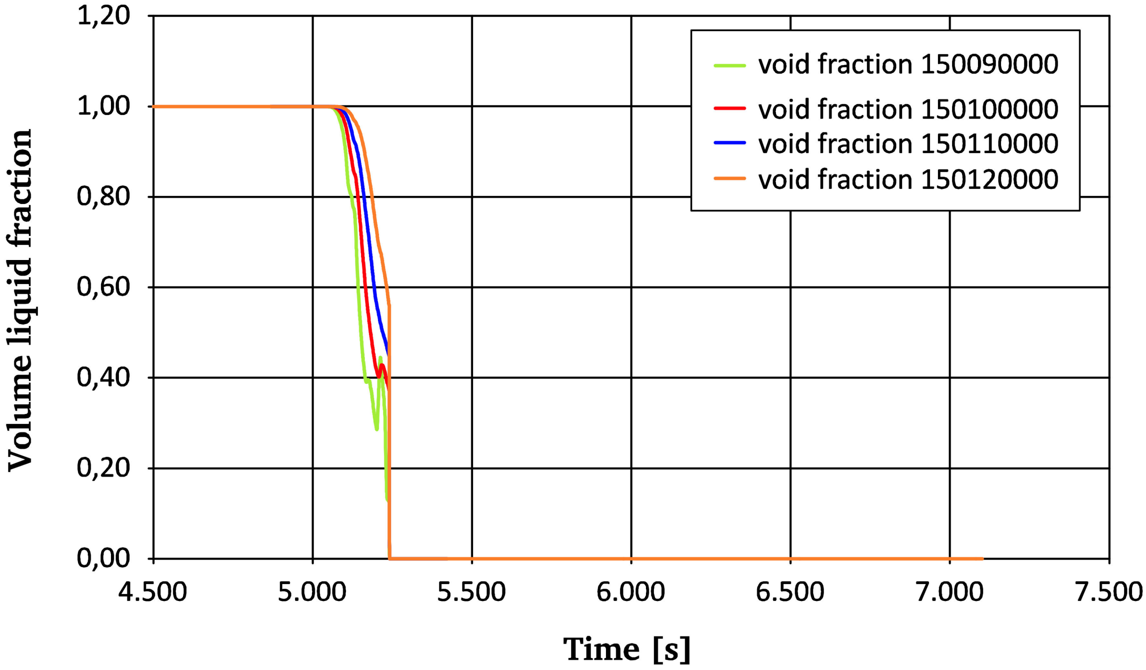

Figure 2. Draining phase in the collector [16].

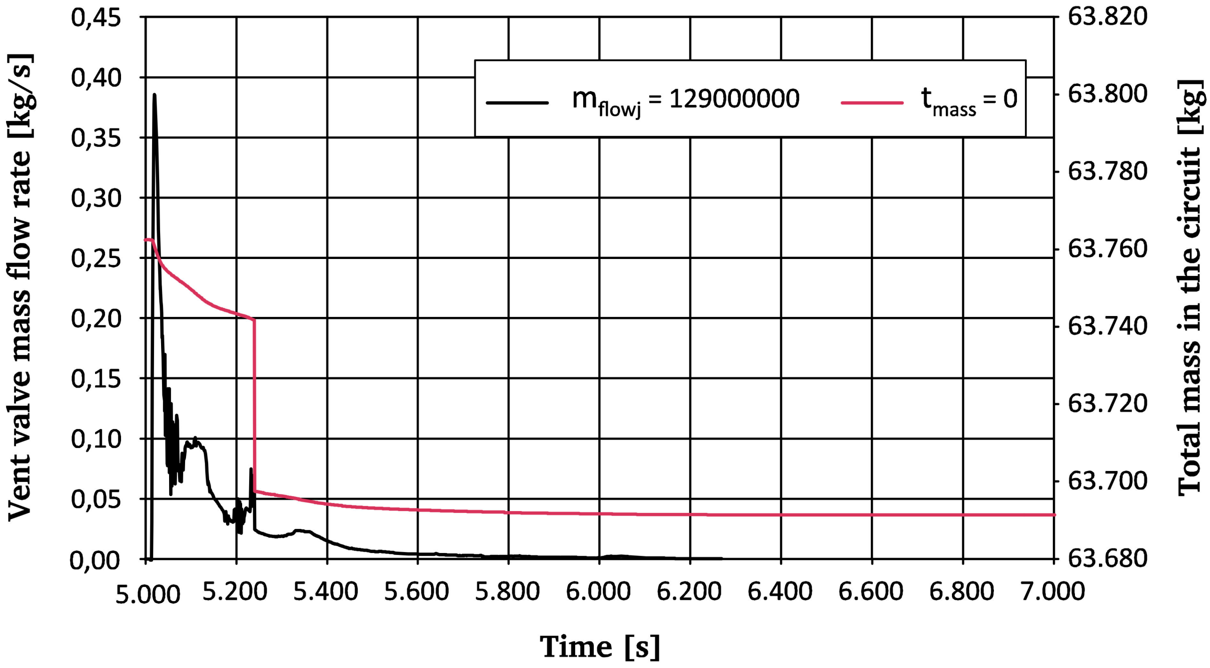

Figure 3. Vent valve mass flow rate and total mass flow in the circuit [16].

El Hefni et al. [36] demonstrated a dynamic model of PTPP operating with synthetic oil and DSG linear Fresnel hybrid CCPP using DYMOLA software. Thereafter, forecasts based on the experimental data were verified. The objective of the present approach was to reduce uncertainties in the annual power generation estimates. Xu et al. [37] introduced a dynamic approach that considers the accumulative influence of solar irradiation. This approach was applied successfully during various disturbance situations (such as DNI and demand changes). Janotte et al. [38] explained the capacity of a PTC loop based on transient constraints. A steady-state approach was used for the comparison of the data obtained for approximately one year. Xu et al. [39,40] designed a dynamic simulation model to complete the static testing methodology of the conventional state. Real experiments to test the outdoor conditions were conducted on a wide scale. Mathematically, this model relies on the energy equilibrium of the main elements of the PTC and unsteady procedures under different conditions, such as changes in the solar radiations, incident angle, HTF mass flow, and HTF temperature at the entrance. In addition, two assumptions were applied within that model: firstly, the temperature of absorption tube is uniform; secondly, a relative error of less than 2% should be present in the operating temperature range and the differences in the volume flow. Mosleh et al. [41] modelled and validated a dynamic mathematical collector model depending on the photo-thermal conversion process of PTPP. Combining the verified model with pumps, oil/water heat exchanger, and other existing models, a parabolic trough solar field technology is implemented on the simulation platform. Boukelia et al. [42] presented the artificial neural network algorithm (ANN) with a feed-forward back-propagation learning algorithm and the Levenberg–Marquardt algorithm in order to analyze and improve the technical and economic performance of two PTPPs combined with a thermal storage system and fuel back-up system. The first power plant uses thermal oil as a heat transfer fluid, while molten salt is used in the second power plant. The best designs of both PTPPs are found in the analysis of levelized energy cost using the obtained weights and biases of the best artificial neural network algorithm topology. The technical and economic potential of both plants were compared based on hourly and annual performances. The comparison shows that the annual energy production and capacity factor of the molten salt power plant increases by about 26 % compared to the thermal oil power plant, due to the difference in the transmission of thermal power methods and the aperture area of the solar collector. Moreover, the results indicate that the levelized energy cost of the first power plant (molten salt power plant) is reduced to approximately 13 % compared with the second power plant (thermal oil power plant). Biencinto et al. [1] presented a quasi-dynamic model of a PTPP using the TRNSYS software environment. Direct steam generation technology was used in this power plant. The behavior of the solar field and the power block of a 38.5 MW_{el} PTPP was analyzed by comparing the annual performance of the suggested strategies (sliding pressure and fixed pressure strategies) regarding electrical power production. Both strategies are applied in the PTPP with direct steam generation in order to control the steam pressure. The comparison displays that the sliding pressure strategies are more efficient in terms of net electrical power production than the fixed pressure strategies. Al-Maliki et al. performed some studies [4,10–14,43] in which the 50 MW_{el} Andasol II power plant was also modelled using APROS software with all required automation circuits. In addition to the solar field, a thermal storage system operated with molten salt and a detailed dynamic model of the power block were also carried out in this study. After achieving the model validation, it can be observed that the thermal energy storage provides an almost constant thermal power to the power block, despite small fluctuations in DNI, as shown in Figure 4. Moreover, the power plant is capable of continued power generation for 7.5 h after sunset, due to thermal storage [43]. Detailed dynamics modelling and simulation were carried out for the 50 MW_{el} Andasol PTPP in Spain. A comparison between measured data and simulated results for a single day during strong cloudy days shows good agreement in the period between 9:55 and 17:14. The differences after this period are due to the unknown behavior applied by the operator in particular. As a result of the optimization of the operating strategy, the generation period of electrical power output is improved by around 26% compared to the reference power plant [4].

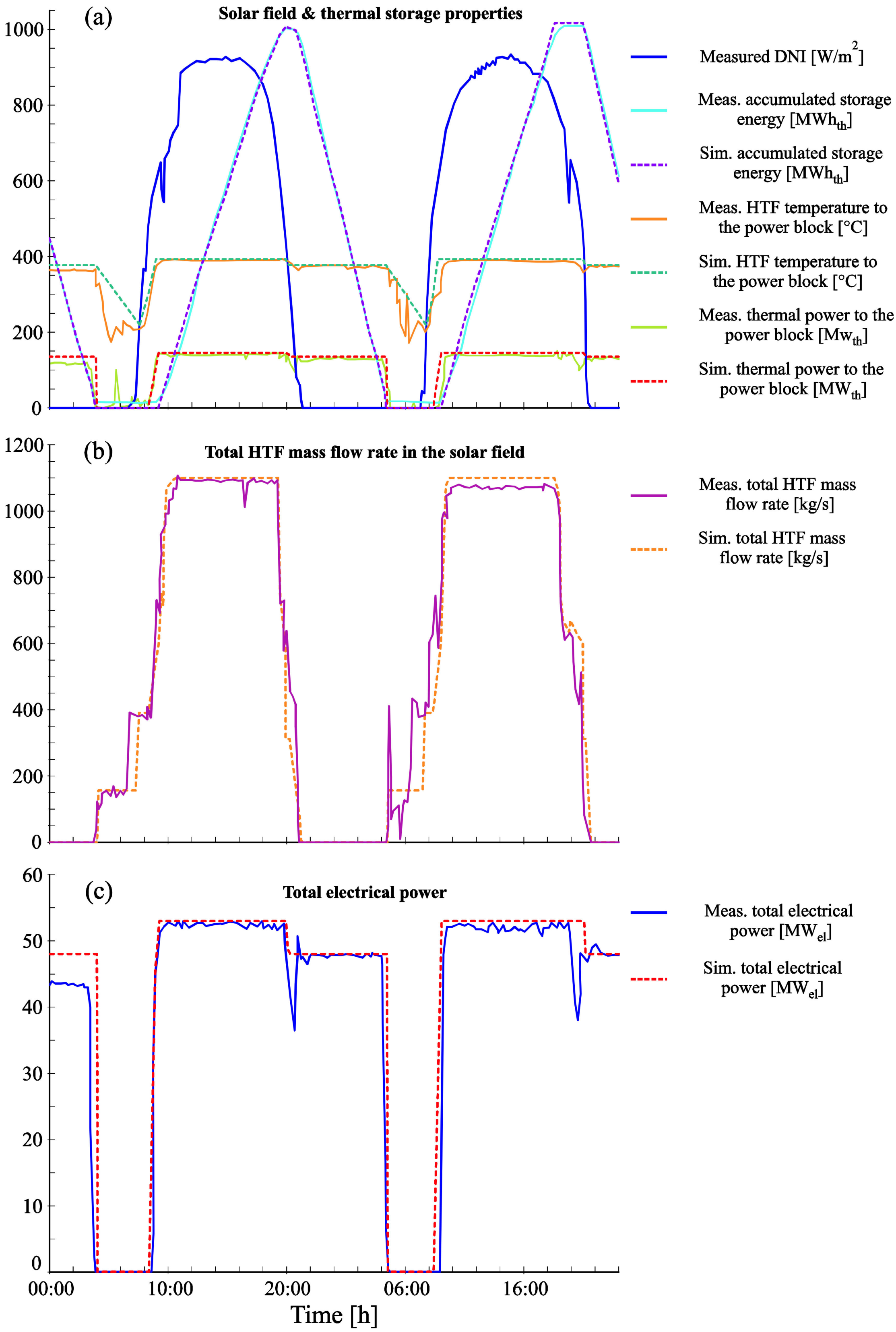

Figure 4. Comparison of measured data and simulated results for clear days [43].

Guo et al. [44] described and evaluated a non-linear dynamic model for the whole solar field of direct steam generation parabolic troughs in the recirculation process. This model simulates and analyses the dynamic approach of the solar field for the recirculation process during weather changes. This model is mathematically solved by the quadratic programming-based constrained GPC method. The control scheme shows a very good performance under different boundary conditions. The simulation results of the model and control system are verified according to the design data obtained from the Direct Solar Steam project. El Ghazzani et al. [45] developed a dynamic model of a small PTPP. The design and control structures of this power plant were implemented using TRNSYS software. The dynamic simulation results were discussed based on various periods demonstrating energetic and exergetic performance data. The main goal of this work was to produce heated air for an industrial factory. The dynamic simulation was carried out according to the solar radiation conditions in Morocco.

Heated air at 150 °C is required for this factory during a daily normal operating period between 8:30 and 00:00 h, all year round. The results show that the CO_2 emissions are reduced by up to 57% per year using this power plant [46–50]. Table 3 shows a comparison between dynamic and steady-state simulation.

Table 3. Comparison between dynamic and steady-state simulation [5].

Steady-State Simulation	Dynamic Simulation
Steady-state simulation is a basis for evaluation, but with limited specifications, which leads to an error rate in evaluating the work of the plant.	Dynamic simulation becomes a powerful means for evaluating regulation approaches, potentialities, and boundaries.
The control circuits are not required.	The control circuits are required.
In the literature, many investigations in regard to the improvement of the PTPP use steady-state simulations.	Few studies deal with a dynamic simulation of power plants.
The solution to the unsteady equation is not required.	Dynamic flow models demand the transient equation solution.
There is no need to consider the time derivatives in the conservation laws.	Sufficient consideration must be given to the temporal derivatives.
It is suitable for applications with stable loads only.	It is considered the best for modelling and evaluating the operation of power stations, which includes changes in loads.

5. Conclusions

Against the background of growing energy needs and environmental pollution problems in the world because of the usage of non-renewable resources, such as fossil fuels, concentrating solar power technologies provide interesting opportunities in countries that have high solar radiation. On the other hand, based on the total electricity production in 2021 and the CSP plants under construction, it can be observed that PTPP are presently the most commercially used technology for producing electricity in the world. Currently, the development trend of this technology globally is obvious in the world, where 70 PTPPs with a gross capacity of 4615 MW_{el} currently exist, as well as 19 PTPPs with a gross capacity of 719 MW_{el} under construction. The objective of this review is to present an overview of the dynamic modelling of PTPP design, evaluation, and optimization. This gives us a greater opportunity for a broad understanding of the PTPPs subjected to a variety of irradiance solar constraints. In addition, the start-up process of the plant, thermal storage system capacities and response dynamics (charging and discharging modes), and yearly electricity yield can be analyzed.

Presented here is a survey of computational dynamic modelling software commonly utilized for commercial and academic purposes, together with several example models of simulation tools such as APROS, DYNAMICS, DYMOLA, and AS-PEN PLUS. The simulation programs are generally based on the conservation equations for mass, momentum, species, and energy. However, specific mathematical expressions are required for the equation of equilibrium, based on the fundamental flow model. Most researchers concentrate on system-level plant dynamics when considering transient solar irradiance. Several other investigations deal with sub-system dynamic behavior, e.g., the thermal storage system, taking into account stable power output and the enhancement in capacity coefficient. When molten salt is used as a heat transfer medium, the filling and discharging processes are analyzed in detail. According to reports, it can improve the operation strategies of these power plants. The time horizons considered in the studies differ from operation time transients of a few minutes to annual performance predictions. A specific focus is on solar field models. A simplified steady-state model is utilized by almost all studies to simulate the solar field or thermal storage, or both, instead of a detailed dynamic model of the power block.

It should be noted that the programs (Ebsilon Professional, Dymola, APROS, etc.) rely on averages of solar values from many previous years on a daily basis, i.e., they cannot provide solar values for a specific year (e.g., 2012, 2013, etc.).

In the future, more attention should be paid to the comprehensive modelling of the whole PTPP, in order to evaluate the dynamic interaction of its components (solar field, thermal energy storage, power block) and the power plant behavior with high accuracy.

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