Dynamic Models of Concentrated Solar Power Plant to Response to Utility Demand Profiles

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Introduction

For a solar power plant, storing energy enables utilities to generate power when and as required and not just when sun is shining. There are two popular ways to convert solar energy to electricity – solar photovoltaic (PV) and solar thermal. In a solar PV plant sun's energy is directly converted to electric energy using solar cells and therefore it requires a battery to store electric energy. A concentrating solar thermal power plant converts solar energy to thermal energy and therefore can store thermal energy which can later be converted to electric energy when required using a turbine generator. Because, today it is cost-effective to store thermal energy than electric energy, solar thermal plants have an advantage. Therefore, there is keen interest from power plant utilities to build large scale concentrating solar thermal power plants (referred to as CSP) that include thermal energy storage (TES).

Power generating utilities prefer the flexibility in electric generating power plants to generate power to match various types of demand profiles from the power grid (this is referred to as the dispatch capability or dispatchability of power plant). The types of demands typically encountered by power grid may include: regulation, day-ahead planned schedules, ramping the power at defined ramp rates and so on. To achieve this, a power plant must respond within seconds to dynamics or changes in power delivered from plant. Therefore, to meet these dynamic response requirements and be acceptable to power utilities, solar thermal plants and hence thermal energy storage subsystem must be designed to be responsive.

There are a number of solar concentrator technologies such as parabolic troughs, power tower, and linear Fresnel reflectors; and there are a number of TES technologies such as sensible heat in solids, sensible in liquids, latent heat in phase change materials, and thermo-chemical heat of reversible chemical reaction. These can be matched in different ways and configured as CSP plants. Also, the size of thermal storage expressed in hours of storage, can be varied to improve capacity factor and dispatch capability of a power plant. For example, a thermal storage expressed as 2-hour storage refers to the ability to generate power at design level on a design day for up to 2 hours using only the thermal energy from thermal storage. However, the power plant dispatcher can use this stored energy at lower power levels for a longer period of time throughout the 24-hour period. Today, most plants are designed to store for up to six hours on a design day. Denholm et al have done an extensive analysis on cost effective sizing of storage for solar plants for various dispatch scenarios. This study provides a more detailed analysis into the dynamics of dispatchability of CSP systems.

CSP systems being built today heat liquids, such as mixtures of molten salts, to a temperature of up to 600 C in solar thermal absorbers and store the hot fluid in a large steel tank. When required to generate power, this hot fluid is pumped out to the power block heat exchangers (PBHX) to generate high pressure steam which is used in turbines to generate power. The cold molten salt fluid from PBHX, typically at 300 C is returned to another carbon steel tank and stored there till it is required again in solar absorbers to collect heat. This type of thermal energy storage (TES) system is referred to as the two-tank sensible heat storage and is currently used in CSP plants under construction at Tonopah, Nevada and in sites in Arizona. This two-tank thermal storage system is easy to operate but is relatively expensive when compared to other TES technologies that are still in development. The aim of these new technologies (described later) is to reduce both cost and size.

While the capital cost of the CSP-TES systems has a profound effect on the life cycle cost of energy (LCOE), the revenue from these systems can be increased if the CSP-TES system can quickly and aggressively respond to specified rate-of-change of power demanded by grid dispatcher. This is because the utilities are allowed to charge more for energy if these plants can be brought on-line or on-grid quickly to respond to demand, especially, during times when the demand for electricity is at its peak. Realizing this, California Energy Commission funded this study to study the dynamic response of various CSP technologies to grid demand.

Thus, cost and response of CSP and TES to demand are important factors in determining the value of CSP-TES to power utility. In order to evaluate the responsiveness of CSP-TES system to various ramp rate power demands, the dynamics of the CSP-TES systems must be understood, modeled and tested against typical utility demand profiles. Therefore, in this study, four utility profiles (described elsewhere in the document) are used to evaluate the effectiveness of combinations of various CSP subsystems (tower, trough, Fresnel etc.) with various thermal storage subsystems.

To compare different TES technologies with a solar concentrator technology, it is essential to optimize the system plant design parameters for each configuration, application and location. These design parameters include solar collector area, number of hours of TES, heat exchanger effectiveness, heat transfer fluid temperature difference across collector and storage, turbine operating hours, TES operating strategy by season, and whether natural gas is used to supplement solar (hybrid plants). The optimum design must consider the capital cost, operations and maintenance cost, and time-of-use value of generated power.

One of the measure for comparing these configurations and technologies is to use levelized cost of electricity (LCOE) and /or annual energy performance. In order to compare and contrast, and select appropriate technology and conduct design trade-offs, developers require dynamic models. These models at a minimum must model the dynamics of components to at least one second interval.

The following paragraphs provide a brief description of the CSP and TES technologies followed by model equations and results for selected TES and CSP technologies.

TES Technologies for CSP Market

As described earlier, the state-of-the-art technique for storing thermal energy uses two tanks to store energy as *sensible heat* in fluids. In this, the hot fluid from solar collectors is first stored in a hot tank. Later after discharging the heat from the hot fluid, the resulting cold fluid is pumped to a different tank. Because the specific heat of the liquids used is low, the two-tank TES requires large amount of fluid and two large tanks and is costly.

To reduce cost and make it more compact, US Department of Energy funded projects to increase the energy density of storage. As part of this, researchers have developed several innovative technologies that can store thermal energy by using the latent heat of fusion in inorganic salts; or technologies that increase specific heat capacity of solids (such as concrete) and technologies that increase the specific heat of fluids. Also, researchers showed that thermal energy can be stored in a single tank using natural thermal stratification in a dual-medium consisting of a solid and a liquid. Recently, US DoE also funded research to use heat of reversible chemical reactions (which is very high) to store energy. Thus, there are really three main technologies – sensible heat storage, phase change material (PCM) storage and chemical energy storage. Chemical storage is not considered because at the time we proposed this project this was still in early research.
The aim of these technologies is to reduce the cost of storage by increasing the energy density of storage (increase energy stored per unit weight or volume of material), because this requires less amount of material and less container. Ten of the TES techniques being considered using sensible heat and phase change heat technologies are depicted in Figure 1 along with the three popular concentrating solar collector techniques.

A good description of the various technologies and techniques of TES is described in literature. Here, we focus on the differences of these TES technologies relevant to our study on dynamic response to changes in load.

Each of the thermal storage technologies when combined with CSP systems has certain nuances and operating constraints that impact the system dynamics and performance. These nuances must be understood and modeled to evaluate the dynamic response of CSP-TES. For example:

- In a two-tank sensible storage system (1 & 2 in Figure 1), the set point for the hot fluid from the CSP system should be at the design temperature at all times. This puts a constraint on the operation of the system during periods of low insolation, requiring the pumping system to be flexible to operate over a wide range of flows. If temperature is lower than the design then the overall generation efficiency decreases.
  In direct two-tank storage, since the heat transfer fluid (HTF) and storage fluid are same, the selection of HTF is based largely on cost because very large volume of fluid are required for thermal storage.
  In an indirect storage system, heat exchangers are required to transfer heat from HTF to charge the storage fluid. This increases cost. Also, thermodynamic efficiency is reduced due to drop in collected temperature and storage temperature. However, the HTF and storage fluid can be selected independently which can reduce cost.

- In a single-tank thermocline system (3,4,&5 in Figure 1), the cost of the system can be lower due to lower cost of container, however, the thermocline degrades and the *utilization factor*, which is a measure of available storage capacity, decreases. The decrease in available capacity to store can be as low as 50% after about 10 partial charge and discharge cycles. To improve the utilization factor, the system must be periodically operated to completely discharge the storage. This lowers the annual efficiency[1]. However, since a dual-media of rock and salt is used the cost of storage media is reduced significantly.
  Terrafore designed an innovative approach to improve utilization factor by actively managing the thermocline diurnally. This patented[2] technique is yet to be demonstrated.
- In a passive latent heat storage system using phase change material (PCM), the heat rate decreases as the solid freezes and builds on the heat transfer tube. The heat exchanger must be designed with a design thickness of solid to be able to deliver heat at the design power rating. A trade-off of quantity of storage material vs. heat exchanger size to maintain a design heat rate requires favors large heat exchangers which drives up cost.
  However, an advantage with a PCM system is that when solar insolation is low, the CSP can be operated at lower than design CSP temperatures to melt the salt which is at a lower than the operating temperature.
- In an active latent heat storage system using PCM[3], the PCM salt is pumped to external heat exchangers to improve heat transfer with partially frozen slurry returned to tank. This requires specially designed heat exchangers and increased pumping power and the amount of heat stored as latent heat is limited since only a fraction of the salt is frozen. However, the overall thermodynamic efficiency and operational efficiency is increased because since large amount of heat is stored at constant temperature and the temperature drop through the thermal storage is small. Terrafore demonstrated this system but determined that it is not practical or economical to use in a large scale solar plant.
- In yet another PCM system, salt is encapsulated in small spheres (microencapsulated) and heat transfer fluid exchanges heat by direct contact with the spheres in a packed bed. The pressure drop through the bed and size of the capsules and hence utilization factor must be traded off. Analysis has shown that the encapsulated thermal storage holds great promise for meeting the cost and performance goals. Terrafore successfully solved the problem of providing an open space in the PCM capsules, to allow the salt to expand on melting.

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[1] To solve this problem, Terrafore is developing an innovative technique in which the thermocline is actively maintained
[2] Terrafore patent application
[3] Ongoing research at Terrafore

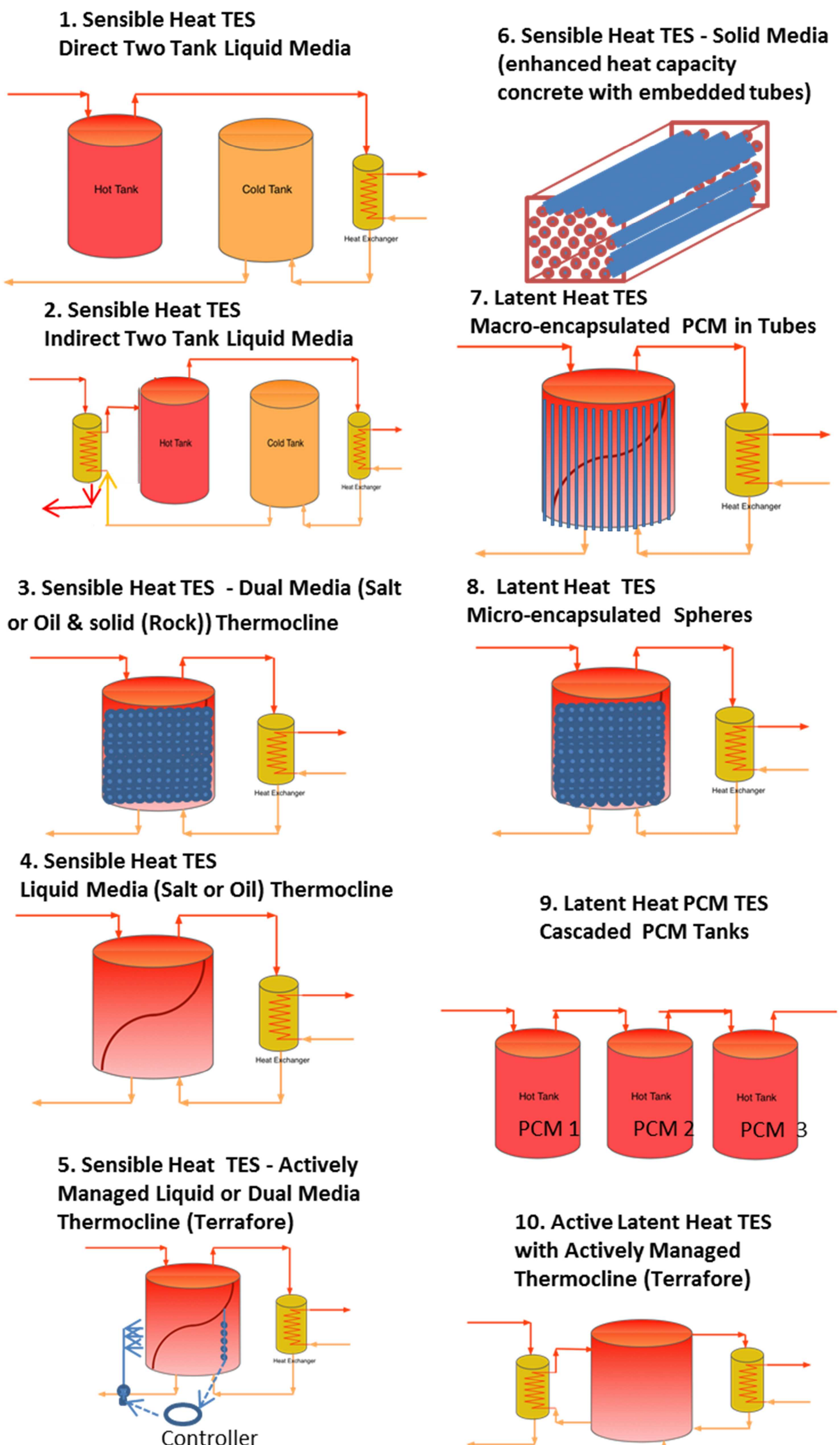


Figure 1. Components of Concentrating Solar Power & Thermal Energy Storage System

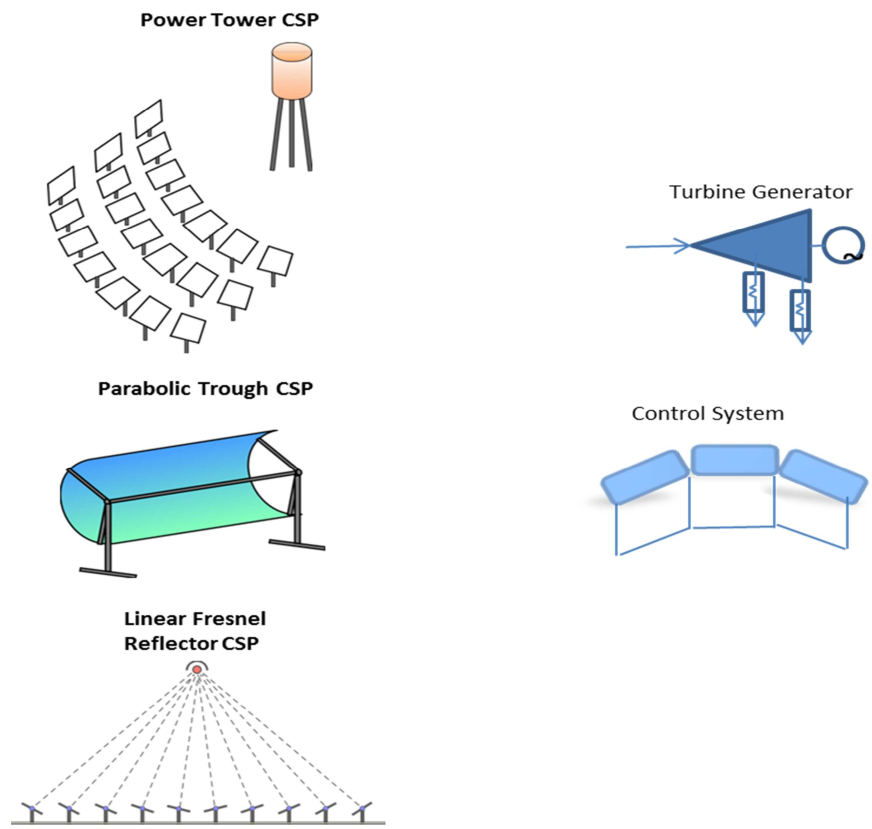


Figure 1 (continued) CSP Receivers and Other Components

Table-1 provides a summary of the key differentiating features of various TES techniques described above. Thus, the thermal storage models for comparing thermal storage systems with different CSP system must have these operational characteristics understood and then modeled.

Amongst the CSP technologies, we modeled the solar tower, parabolic collector and linear Fresnel collector system. Parabolic dish CSP systems are point-focus and typically use Stirling engine at the focal point of the collector to generate power directly. These systems are being designed to have a very little[4] dispatchable PCM storage built into the receiver, to aid in smoothing the thermal transients due to sudden changes in solar insolation. Even though dish systems can provide better stable and predictable power than photovoltaic systems, they are still in development and not yet popular.

The CSP tower considered is a cylindrical absorber on top of a tower cooled using molten salts (for example, Solar Reserve is building an absorber/ receiver atop a 680 ft. tower at Tonopah, Nevada). Other types of CSP power tower uses cavity receivers to heat air or particles to very high temperature which can then be used with combined cycle or Brayton cycle power generation. These systems, still in development, operate at very high temperatures (~1000 C) and typically use solid media sensible heat storage. To limit the scope of, only molten salt tower models were developed.

[4] Infinia is developing a Dish system that uses a small amount of PCM in the receiver

Mathematical models to study parametric effects on design and thermal dynamic response of sensible and latent heat system have been widely studied. There are several papers on packed bed sensible heat storage, packed bed latent heat storage in PCM, thermal stratification models (Schumann equations) for storing sensible heat in liquids and dual media. An institute in Germany [1] is investigating sensible heat in concrete with embedded fibers to enhance specific heat. Also a cascaded PCM thermal storage in multiple tanks using PCMs with progressively higher melting points has been studied (the lower melting point is used to store energy to provide for vaporization of water and higher melting point PCMs are used for superheating steam). The bibliography [1 to 16] provides a partial list of selected papers relevant to our proposed approach. Literature describes the fundamental heat and mass transport models for each of the selected storage system. In as far as possible we used the available literature models in our study but included the dynamics to model the relevant operational characteristics that impact selected utility profiles.

Table-1 provides a summary of the key differentiating features of various TES techniques.

Table1. **Features relevant to dispatchability[5] of various TES Technologies**

	TES Technology	Maturity Level [1]	Near Term [2]	Commercial Potential	Key features of TES relevant to grid-wise impact & dispatchability[5]
1	Two Tank direct (Sensible TES)	H	H	H	Temperature in hot tank decreases slightly as tank is discharged. This results in reduced heat rate or availability of stored energy. If molten salt is used as storage medium, there is a potential for the salt to freeze, when tank is discharged to below 20% capacity. This impacts operation, storage maintenance cost, and deliverable energy & power.
2	Two Tank Indirect (Sensible TES)	H	H	H	Same as two tank direct. Since heat is transferred through an external heat exchanger, there is a decrease in thermodynamic efficiency of system and sluggish thermal response.
3	Dual Media Thermocline (Sensible TES)	M	H	H	Same as 1a. Hot and cold temperatures cannot be large. Large sudden temperature variations can cause thermal ratcheting. Tank costs can be high and size can be limited.

4	Molten Salt tank thermocline (Sensible TES)	M	M	H	Thermocline degrades with partial charge discharge, mixing at fluid inlet, and near tank walls. This will result in uncertainty in the delivered heat rate as a function of stored capacity and time.
5	Actively Managed Thermocline (Sensible TES)	L	M	L	Solves the issues with partial charge and discharge in 3... But mixing of fluid near point of fluid extraction can degrade performance. Not yet demonstrated in practice.
6	Solid Media (Concrete) (Sensible TES)	M	H	M	Heat rate decreases as a function of stored energy. Transient dynamics as function of storage state must be understood and modeled. Research is underway to increase thermal conductivity of concrete. However, there are still several practical issues with system design and imperfect contact of concrete with heat exchanger tubes. Not yet a mature technology.

	TES Technology	Maturity Level [1]	Near Term[2]	Commercial Potential	Key features of TES relevant to grid-wise impact & dispatchability[5]
7	Passive Heat Exchange with PCM in tubes (Macro-encapsulated Phase change)	M	M	M	Heat rate decrease as heat is extracted from the storage media due to solidification of material on heat exchanger tubes. Transient behavior as function of state of charge must be understood and modeled. Must measure or infer the state of charge to predict heat rate. Requires other means to superheat steam (for example auxiliary heat using natural gas)
8	Cascaded encapsulated PCM TES in small spheres or capsules (micro-encapsulated phase change)	M	M	H	Performance can be expected to be close to two tank sensible heat storage while costs can be reduced by 50%. Terrafore successfully made capsules containing PCM salt which expand without rupturing the shell. By encapsulating salts at different melting points and cascading in same tank they showed the costs can be lowered by 40%.Potential to scale system to base load CSP if cost of making capsules is reasonable. Still need to demonstration scale-up to make capsules in large quantities.

9	Cascaded Passive PCM Storage in multiple tanks	M	M	M	Same as above. However, costly due to multiple tanks. Parasitic power an issue especially when turbine is operated at low power.
10	Indirect Active Heat Exchange PCM	L	L	L	Research at Terrafore successful in freezing 30% of salt. . However, both heat transfer rates and storage capacity can decrease with time. Many engineering problems with pumping freezing salt mixture. Not practical...

Note: for column headers in table.

1. Technology maturity level
2. Chances of technology being deployed in near term (5 years)
3. Are reasonable fidelity models available in Literature
4. See Bibliography for references. Bold represent model we will likely select
5. Remarks are either characteristics of the TES or gaps in the available models that will be addressed

Approach to Mathematical Modeling

The steps to modeling, shown in Figure 2, include the following:

- Determine the system design parameters to meet the design requirements. For this, we will use the system design model existing with Terrafore.
- Develop component models in Matlab by coding the model equations
- Construct a simulink model for each configuration using the component models.
- Integrate into the KEMA code for grid-wise impact analysis

The models for sensible heat in hot and cold tank are straightforward and there is adequate experience with these systems to define constraints and recoverable storage volumes. Comprehensive list of models for various types of packed bed thermal storage for both sensible and phase change materials are provided in literature[3] . Since these systems are still being developed to be used with CSP, we plan to do a more detailed development of these and tailor them for use with CSP system.

Terrafore has developed dynamic models for PCM storage in capsules (~5mm to 10mm diameter) to evaluate heat transfer in packed beds which is used in this analysis. An analysis of thermal response of packed bed of PCM capsules is also provided in [2].

Thermal stratification has been demonstrated in laboratory scale. However, it is generally recognized that in large scale application, maintaining thermal stratification is very difficult. Thermocline degrades significantly with partial charge and discharge cycles (Terrafore' s internal study has shown that in 10 cycles the utilization factor goes from 85% to 40%). Also mixing of fluid at entrance and exit of the tank can reduce temperature and quality of heat available for discharge. To accurately model these, one needs to use a Computational Fluid

Dynamics package which is too detailed for the scope of this project. Instead, we modeled the mixing using simple equations.

In an encapsulated PCM storage (not yet used in commercial CSP), the heat transfer inside the capsule can be through conduction and through convection or a combination of the two. Since there is a void inside the capsule, the heat transfer through the capsule is modeled using two-phase models.

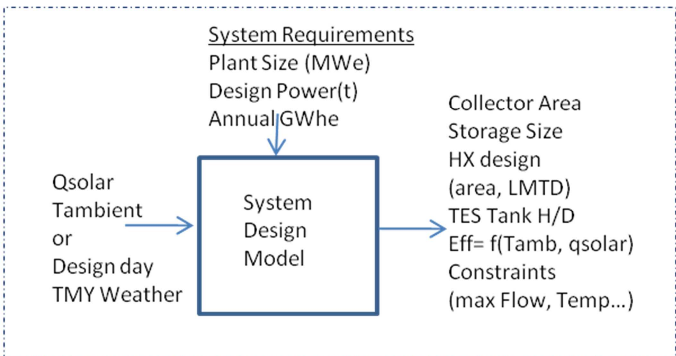
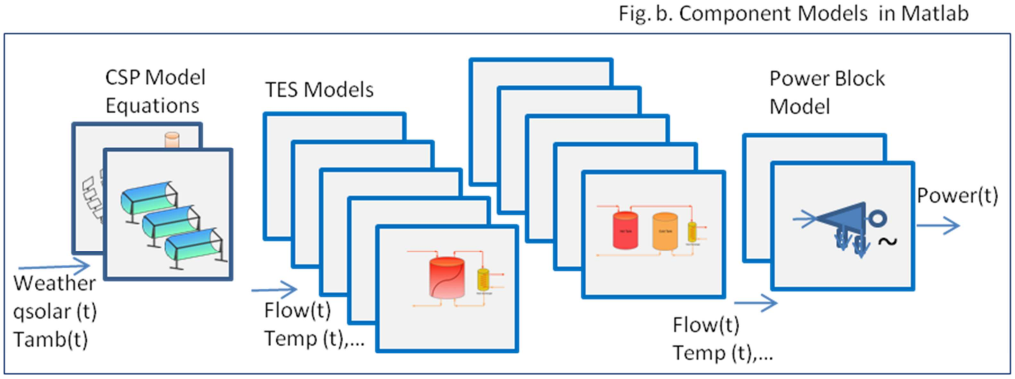


Fig.a. Output from Terrafore's system design model to component models

Fig. b. Component Models in Matlab



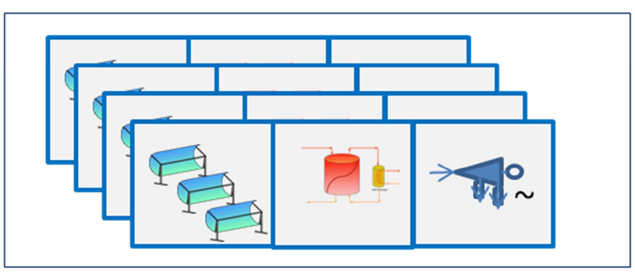


Fig. c. Simulink Models System Configurations

Figure 2. Approach to Mathematical Modelling