CSPBankability Project Report

Draft for an Appendix G – Electrical System

to the SolarPACES Guideline for Bankable STE Yield Assessment

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Index of contents

G. Electrical System Modeling

G.1. General

The purpose of this appendix is to provide an overview of the major aspects of the electrical system of a CSP plant which are relevant for annual yield assessments. More precisely, the electrical system is of importance when trying to determine the net electrical output of the CSP plant after having calculated the gross electrical output as described in detail in Appendix D of the Guideline.

The electrical system is defined here as the electrical transmission, distribution and transformation system, which has mainly the following tasks:

- Transmission of the produced electric power to the public grid
- Distribution and transformation of a part of the generated electricity to supply all electrical consumers of the plant

The interfaces of the plant's electrical system are typically as follows:

- Generator terminals
- Grid connection point
- Consumer terminals

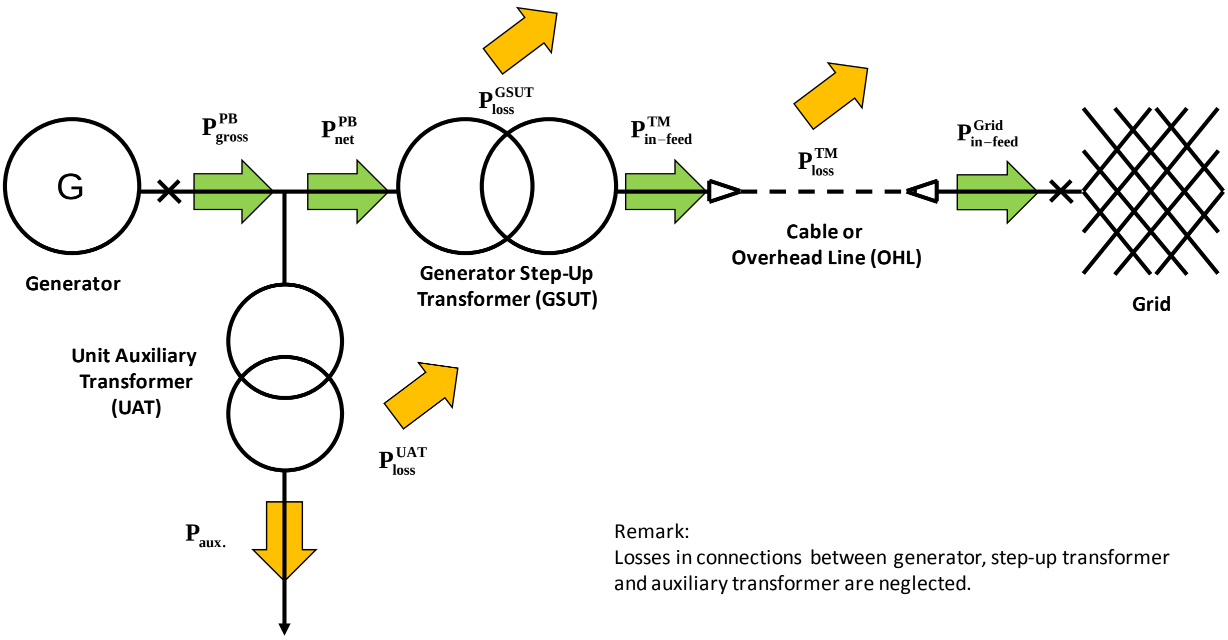

Figure G-1: Simplified single line diagram and losses of electrical system for normal operation

The electrical system consists mainly of transformers, switchgear, busbars, cables, Uninterrupted Power Supply (UPS) system, stand-by diesel generators, e-motors, protection and synchronization devices, earthing and lightning protection system as well as lighting and other smaller auxiliary power systems. In some projects, additional assets like a dedicated substation are required, which lead to increased total investment costs of a project.

Another cost driving factor is redundancy. Redundant technical systems are required to ensure safe and continuous plant operation, they increase investment costs and at the same time increase system reliability. Redundant electrical supplies are often requested for plant sections that are vital for plant operation, or to mitigate high risks of plant shutdown and longer plant unavailability due to damaged equipment which needs to be repaired or replaced. This common approach provides a good balance between investment costs and plant reliability. As an example, the back-up emergency diesel generator is a stand-by power unit for supply of electrical energy to the molten salt heaters to avoid crystallization of the medium at all times.

Electric power injected into the electrical system by the generator is reduced on its way to the grid connection (and metering) point by the auxiliary electrical consumption of the plant as well as the losses caused by the electrical system itself as defined below and depicted in Figure G-1.

$$P_{in-feed}^{Grid} = P_{gross}^{PB} - P_{aux.} - P_{loss}^{UAT} - P_{loss}^{GSUT} - P_{loss}^{TM} \quad \text{(G.1)}$$

P_{gross}^{PB}	Gross capacity of power block @ generator terminals
$P_{aux.}$	Auxiliary electrical consumption of the plant
P_{loss}^{UAT}	Electrical losses of Unit Auxiliary Transformer (UAT)
P_{loss}^{GSUT}	Electrical losses of Generator Step-up Transformer (GSUT)
P_{loss}^{TM}	Electrical losses in transmission line from GSUT up to grid interconnection point

Note: For simplification purposes the reactive power is neglected.

P_{gross}^{PB} is an output value from the powerblock model as described in Appendix D. The modeling approaches for the performance-related and economically relevant losses are briefly described in the next sections.

G.2. Auxiliary electrical consumption

The net capacity of the Power Block (PB) is determined by the PB gross capacity and the auxiliary electrical consumption of the plant's electrical consumers. Basically, for each project the electrical consumers are to be detailed in the electrical consumer list of the plant. These consumers and their requirements vary depending on type, size, configuration and location of the project.

In general, the main electrical consumers of an Solar Power Plant are

- Power Block
    - Condensate extraction pumps
    - Feedwater pumps
    - Main cooling pumps
    - Cooling fans for Air Cooled Condensers (ACC) or forced draft fans of wet cooling tower (as applicable)
    - Power block auxiliaries
        - Instrumentation & control
        - Steam Turbine auxiliaries (lube/control oil system etc.)
        - Closed cooling water system
- Balance of Plant
    - Raw water intake/wells (as applicable)
    - Water treatment plant
    - Service water system
    - Compressed air system
    - Auxiliary steam generator
    - Firefighting and detection system
    - Building/plant auxiliaries
        - Heating, ventilation and air conditioning (HVAC)
        - Lighting
        - Closed circuit television (CCTV)
        - other security systems
- Solar Field - collector drives incl. I&C (meters etc.)
- HTF system
    - HTF main pumps
    - Auxiliary HTF pumps
        - Freeze protection
        - Solar field recirculation (as applicable)
    - Secondary HTF pumps
        - Overflow return
        - HTF storage
        - HTF heater (fans, fuel pumps etc.)
        - HTF ullage system
        - etc.
    - Heat tracing
    - Miscellaneous auxiliaries of HTF system
- TES system

- Molten salt main pumps
- Molten salt secondary pumps (as applicable)
- Electrical immersion heaters
- Heat tracing system
- Miscellaneous auxiliaries TES system

The auxiliary electrical consumption of the electrical system itself for control voltage, battery system, distribution transformers, transformer cooling systems and similar minor consumers can be neglected.

With regard to yield prognosis calculations a distinction must be made between electrical consumption characteristica of on-line and off-line consumers. The electrical consumption of most main consumers is load-dependent, thus can be easily implemented in the yield prognosis calculations, provided that the partload characteristics of the consumers are known. On the other hand, some consumers are operating only when the plant is off-line like e.g. heat tracing and electrical immersion heaters of the TES system.
In case of consumers where the electrical demand is not easily determinable (e.g. ullage pumps of the HTF system), a simplification can be done by means of considering a single-digit percentage of the total predictable demand of the main consumers in relation to the gross plant capacity (see example at the end of this section). It must be noted that this approach requires project experience and a case-by case investigation.
Information regarding the major subsystems of the plant, namely power block, solar field, storage and auxiliary heater as well as their associated main electrical consumers can be found in the corresponding Appendices.

The total auxiliary electrical consumption of the plant $P_{aux.}$ can be calculated from the aforementioned project-specific consumer list as follows:

$$P_{aux.} = P_{aux.}^{SF} + P_{aux.}^{TES} + P_{aux.}^{PB} + P_{aux.}^{BoP} + P_{aux.}^{Other} \quad \text{(G.2)}$$

$P_{aux.}^{SF}$	Auxiliary electrical consumption of SF and HTF system
$P_{aux.}^{TES}$	Auxiliary electrical consumption of TES system
$P_{aux.}^{PB}$	Auxiliary electrical consumption of PB
$P_{aux.}^{BoP}$	Auxiliary electrical consumption of BoP systems
$P_{aux.}^{Other}$	Auxiliary electrical consumption of other systems (e.g. electrical system)

The amount of total auxiliary electrical consumption of the plant varies mainly as a function of

- plant performance parameters

- plant configuration, e.g. with and w/o TES
- cooling system design
- location and ambient conditions
- grid requirements and operation strategies

As an example, for a CSP plant located on the Arabian Penninsula with 50 MW gross capacity, large Thermal Energy Storage (TES) and Parabolic Trough Collector (PTC) technology with synthetic oil as Heat Transfer Fluid (HTF), the auxiliary electrical consumption can be estimated in the range between 10 to 13% of the installed gross capacity. The figure below shows the corresponding distribution of the total auxiliary electrical consumption to the major systems for this exemplary CSP plant.

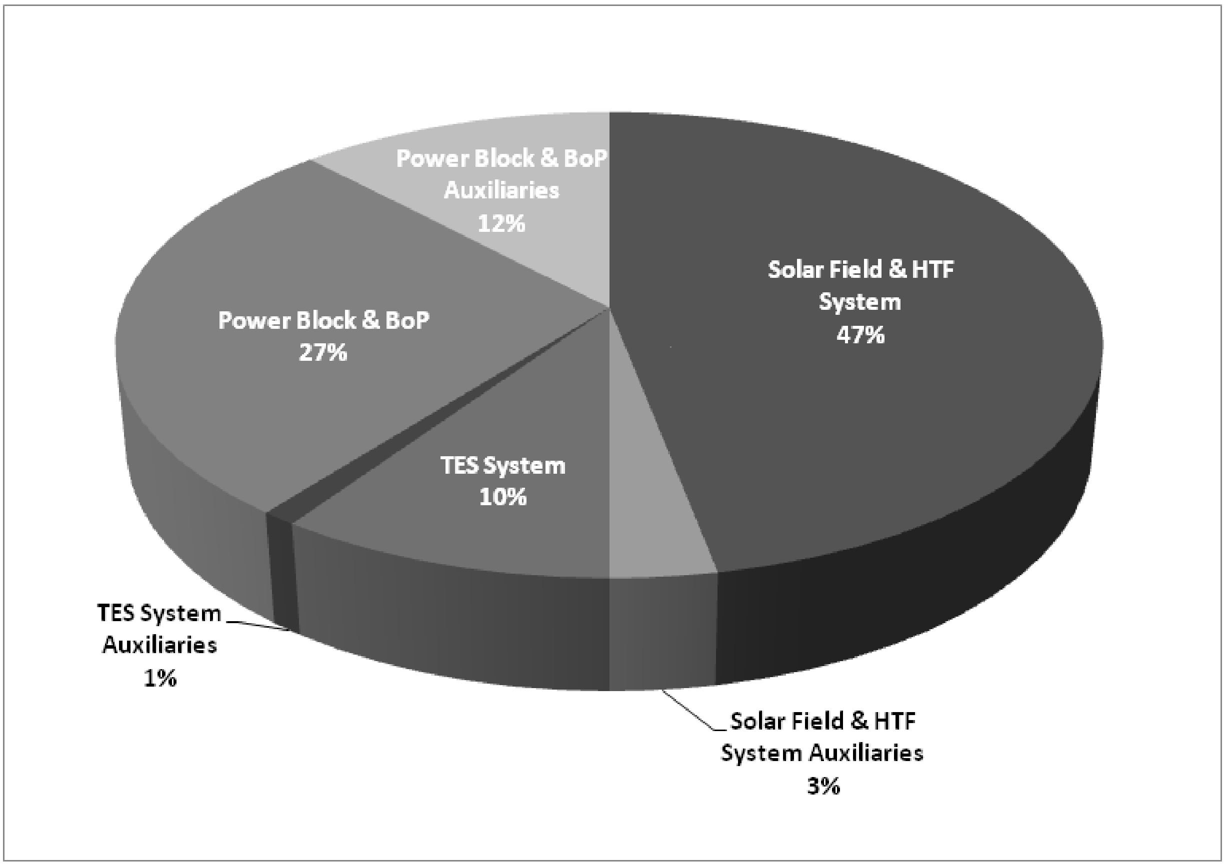

Figure G-2: Auxiliary electrical consumption share of major CSP plant subsystems for a reference case

The exemplary figure shown above represents the auxiliary electrical consumption of the main components (e.g. main pumps) and auxiliaries such as I&C systems of the SF, HTF and TES systems as well as of the PB and BoP systems. The proportion of the consumption of auxiliaries for the main systems amounts to 4 % of the total auxiliary electrical consumption for SF, HTF and TES systems, whereas the auxiliaries of the PB and BoP systems consume approx. 12 %[1].

[1] @ Reference Site Conditions (RSC) with max. load from SF to PB and TES

STE plants basically are shut down during night, which means that electricity must be obtained from the grid. In this case the generator ciruit breaker opens and the electricity for the plant internal off-line consumers is directed from the grid via the GSUT and UAT. For simplification purposes, the annual amount of energy from the grid can be can be assumed in the range of 12 to 18 % of the annual auxiliary electrical consumption of the plant. Note that this energy amount would theoretically be purchased from the utility, wherefore it must be accordingly separated from the annual sum of the load-dependent auxiliary electrical consumption.

G.3. Transformer losses

Major transformer losses depend basically on

- total power P_{net}^{PB} injected into the GSUT and
- total auxiliary electrical power from the UAT

The total transformer losses consist of load losses and no-load losses for each transformer. Load-losses primarily depend on the electrical conductivity of transformer main coils, whereas no-load losses essentially depend on the magnetization characteristic of the transformer's magnetic core.

For practical reasons, GSUT losses can be approximated as follows:

$$P_{loss}^{GSUT} = P_{loss,no-load}^{GSUT} + P_{loss,load}^{GSUT} \left(\frac{P_{net}^{PB}}{S_n cos\varphi} \right)^2 \quad \text{(G.3)}$$

or

$$P_{loss}^{GSUT} = P_{loss,no-load}^{GSUT} + P_{loss,load}^{GSUT} \left(\frac{P_{gross}^{PB} - P_{loss}^{UAT} - P_{aux.}}{S_n cos\varphi} \right)^2 \quad \text{(G.4)}$$

and for the UAT the approximation is

$$P_{loss}^{UAT} = P_{loss,no-load}^{UAT} + P_{loss,load}^{UAT} \left(\frac{P_{aux.}}{S_n cos\varphi} \right)^2 \quad \text{(G.5)}$$

with

S_n	Transformer rated power (IEC definition)
$cos\varphi$	Actual power factor[2]

In the following, exemplary values for transformer losses are presented which can be used for initial analysis.

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[2] Actual power factor is defined as the ratio of active power *P* in (watts, W) to the apparent power *S* (volt-amperes, VA). Active power corresponds to the real power of a circuit which can perform work, whereas apparent power is determined by the product of the circuit voltage and current. As a result of interaction of the electrical load in the circuit with the load source, the real power is lower than the apparent. In principle, the power factor of an electrical power system will be defined by the national grid code in order to ensure a certain electrical system quality. For the subject exemplary analysis, the actual power factor amounts to 0.9.

Table G-1: Exemplary values for GSUT losses

$\boldsymbol{Voltage\ Level}$	kV	66			132		220	420
$\boldsymbol{S_n}$	MVA	82	103	124	164	208	100	200
$\boldsymbol{P}$	MW	73.5	92.7	111.6	147.6	187.2	90	180
$\boldsymbol{P_{loss,no-load}^{GSUT}}$	kW	34.4	37	36	68	111	15	120
$\boldsymbol{P_{loss,load}^{GSUT}}$	kW	222	390	413	432	376	200	646

Table G-2: Exemplary values for UAT losses

$\boldsymbol{Voltage\ Level}$	**kV**	15.75			
$\boldsymbol{S_n}$	MVA	16	35	40	50
$\boldsymbol{P}$	MW	14.4	31.5	36	45
$\boldsymbol{P_{loss,no-load}^{UAT}}$	kW	14	22.7	24	28
$\boldsymbol{P_{loss,load}^{UAT}}$	kW	114	92	160	180

Please note that the above given reference values for transformer losses have been derived from project and manufacturer specific data. Further, it should be noted that manufacturers have the possibility of adjusting losses in a certain range through material selection and material quantities as well as adaptation of transformer design.

Basically, the selection of a GSUT depends on the transformer power factor ($cos\varphi$) and the net capacity of the plant P_{net}^{PB}, which in turn is to be determined by substraction of the theoretical auxiliary electrical consumption from the installed capacity:

$$S_n = \frac{\boldsymbol{P}_{gross}^{PB} - \boldsymbol{P}_{aux.}}{\cos\varphi} \quad \text{(G.6)}$$

In case of the UAT, the selection should be based on

$$S_n = \frac{\boldsymbol{P}_{aux.}}{\cos\varphi} \quad \text{(G.7)}$$

As a rough estimation, the total transformer losses are in the range of 0.3 to 0.5% of the gross plant capacity.

G.4. Power transmission losses

Losses caused by the power transmission line on the path from GSUT to the grid connection (and metering) point depend primarily on the total power $P_{in-feed}^{TM}$ injected into the transmission line.

The total transmission line losses consist of its specific load losses and no-load losses. Load-losses primarily depend on the resistance and inductance per unit length of the transmission line, whereas no-load losses essentially depend on conductivity and capacity per unit length of the transmission line. In addition, transmission line losses generally increase with increasing length.

Power transmission to the grid connection (and metering) point can either be implemented via underground cable, Overhead Line (OHL) interconnection or a sequence of both types.

For practical purposes, power transmission line losses can be approximated as follows:

$$P_{loss}^{TM} = \left(p_{loss,no-load}^{TM} + p_{loss,load}^{TM} \left(\frac{P_{in-feed}^{TM}}{S_n cos\varphi} \right)^2 \right) l \qquad \text{(G.8)}$$

or

$$P_{loss}^{TM} = \left(p_{loss,no-load}^{TM} + p_{loss,load}^{TM} \left(\frac{P_{gross}^{PB} - P_{aux.} - P_{loss}^{GSUT} - P_{loss}^{UAT}}{S_n cos\varphi} \right)^2 \right) l \qquad \text{(G.9)}$$

where

S_n	Tranmission line rated power (design power)
l	Length of transmission line

Power transmission capability and losses of a cable connection depend to a large extent on its installation conditions. Amongst others, these are

- length
- conductor type and cross section
- method of laying
- shielding
- ambient and ground temperature and
- ground thermal resistivity

The table below shows exemplary loss values. More accurate values of power transmission capability and losses of a cable connection have to be determined on a case-by-case basis.

Table G-3: Exemplary values for transmission line cable losses

$Voltage\ Level$	kV	110	220	380
S_n	MVA	110 to 280	340 to 550	690 to 1380
$p_{loss,no-load}$	kW/km	≈ 2	≈ 7	≈ 10
$p_{loss,load}$	kW/km	20 to 100		40 to 160

Similar to High Voltage (HV) cables, the installation conditions determine the power transmission capability and losses of an Overhead Line (OHL) connection. Conditions which have an effect on the performance characteristics, inter alia, are

- length
- conductor type and aerial cable cross section
- wind and ice loads
- span widths between masts
- voltage levels
- required current carrying capacity

Exemplary values for OHL interconnection losses based on data compiled from project experience values are given below.

Table G-4: Exemplary values for OHL interconnection losses

$Voltage\ Level$	kV	110	220	380
$Conductor$	-	**Al/St 264-AL1/34-ST1A**		**4 x 264-AL1/34-ST1A**
S_n	MVA	260	520	690 to 1380
$p_{loss,no-load}$	kW/km	< 0.5	≈ 2	≈ 3
$p_{loss,load}$	kW/km	≈ 390		90 to 350

G.5. Calculation example for electrical losses

In order to illustrate the previously introduced approximations for electrical losses and performances, this section presents a calculation example with following assumptions:

Table G-5: Technical assumptions for exemplary electrical loss calculation

Item/Description	***Symbol***	***Value***	***Unit***
PB gross capacity	P_{gross}^{PB}	100	MW
Operation condition	-	design	-
Power factor	$\cos\varphi$	0.9	-
Distance to grid connection point	l	20	km
Voltage level	-	110	kV
Total auxiliary electrical consumption of the plant*	$P_{aux.}$	13	MW

* Determined on sub-system level calculations (refer to appendices of sub-systems)

The calculation steps to obtain the total power injected into the grid P_{net}^{Grid} at the grid connection point are depicted in the following.

(1) Selection of UAT reference from Table G-2:

$$S_n = 16\ MVA$$

(2) Calculation of UAT losses with equ. (G.5):

$$P_{loss}^{UAT} = 14\ kW + 114\ kW \left(\frac{13\ MW}{16\ MVA * 0.9}\right)^2 \approx 107\ kW$$

(3) Selection of GSUT reference from Table G-1:

$$S_n = 124\ MVA$$

(4) Calculation of GSUT losses with equ. (G.4):

$$P_{loss}^{GSUT} = 36\ kW + 413\ kW \left(\frac{100\ MW - 0.107\ MW - 13\ MW}{124\ MVA * 0.9}\right)^2 \approx 286\ kW$$

(5) Calculation of transmission line losses for a voltage level of 110 kV based on an OHL connection with equ.(G.9):

$$P_{loss,TM}^{TM} = \left(0.5\ \frac{kW}{km} + 390\,\frac{kW}{km}\left(\frac{100\ MW - 13\ MW - 0.286\ kW - 0.107}{260 * 0.9}\right)^2\right) 20\ km = 1078\ kW$$

(6) Calculation of power fed into the grid at connection and metering point with equ. (G.1):

$$\boldsymbol{P_{in-feed}^{Grid}} = 100\ MW - 13\ MW - 0.107\ MW - 0.286\ MW - 1.078\ MW = \mathbf{85.5}\ \boldsymbol{MW}$$

List of figures

List of tables

List of formula symbols

$P_{aux.}$	Total auxiliary electrical consumption of the CSP plant [MW]
P_{gross}^{PB}	PB gross output [MW]
P_{loss}^{GSUT}	Generator Step-up Transformer (GSUT) losses [kW]
P_{loss}^{TM}	Transmission line losses [kW]
P_{loss}^{UAT}	Unit Auxiliary Transformer (UAT) losses [kW]
$P_{loss,load}^{GSUT}$	Load losses of GSUT [kW]
$P_{loss,load}^{UAT}$	Load losses of UAT [kW]
$P_{loss,no-load}^{GSUT}$	No-load losses of GSUT [kW]
$P_{loss,no-load}^{UAT}$	No-load losses of UAT [kW]
$P_{in-feed}^{TM}$	Net power delivered to the HV transmission line [MW]
$P_{in-feed}^{Grid}$	Net power fed into the grid at connection and metering point [MW]
P_{net}^{PB}	PB net output [MW]
S_n	Transformer rated power (IEC definition) [MVA]
$p_{loss,load}^{TM}$	Specific load transmission line losses [kW/km]
$p_{loss,no-load}^{TM}$	Specific no-load transmission line losses [kW/km]
$cos\varphi$	Actual power factor [-]
l	Length of transmission line [km]

List of abbreviations

ACC	Air Cooled Condenser
CCTV	Closed Circuit Television
GSUT	Generator Step-Up Transformer
HTF	Heat Transfer Fluid
HV	High Voltage
HVAC	Heating, Venting and Air Conditioning
OHL	Overhead Line
PB	Power Block
SF	Solar Field
CSP	Concentrated Solar Power
TES	Thermal Energy Storage
TM	Transmission
UAT	Unit Auxiliary Transformer
UPS	Uninterrupted Power Supply