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Numerical Simulation of a Steam Pipeline Network Using Dymola®

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ABSTRACT

This paper focuses on the simulation and performance analysis of a steam pipeline network located in the so-called “traditional” geothermal area of Tuscany.

The area hosts a steam-dominated geothermal system characterized by the presence of shallow and deeper reservoirs with different temperature and pressure conditions. The pipeline network examined counts of more than a hundred of branches and supplies steam produced by 37 wells of the area to 8 power units with a total of 200 MWe installed.

A model of this steam pipeline network was developed in the simulation environment Dymola® using both Modelica Standard Library elements and others specifically created. The model is capable of simulating the steady-state behavior of the network in terms of pressure drops, mass and energy flow rates, and heat losses using as inputs the well and turbine characteristic curves as well as the main pipeline network technical specifications.

Once validated against the actual field operating data in order to check the accuracy of the modeling process and ensure the model reliability, the model could be used to support the operation in maximizing the power generation by means of a proper distribution of the steam flows or in verifying a-priori the effects of maneuvers on the steam pipeline network.

A case study of interest is presented with the aim of illustrating the main features of the model and to demonstrate its potentialities in the context of steam pipeline network performance analysis.

The conclusions of the work are drawn pointing out which possible improvements can be implemented in order to increase the model accuracy in predicting the actual behavior of the network and extend its areas of application.

1. INTRODUCTION

Italy is the first European geothermal nation by net generation capacity and the seventh internationally behind United States, Indonesia, Philippines, Turkey, New Zealand and Mexico (IRENA, 2019). Enel Green Power, the Enel Group company that develops and manages energy generation from renewable sources at a global level, is currently the only geo-electricity producer of the country operating 37 power units for 915.5 MWe totally installed. Most of them, 30 groups for 794.5 MWe installed, are located in the traditional geothermal area of Tuscany, in the west part of the region among the provinces of Pisa, Siena and Grosseto (Manzella et al., 2019).

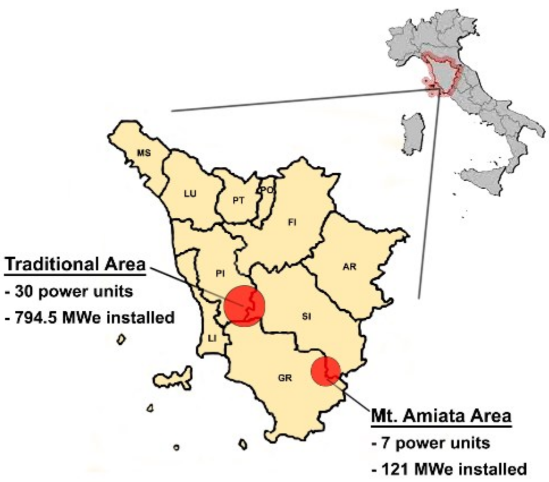

Figure 1: Location of Tuscany traditional geothermal area.

The power plants of this area are fed with steam produced by almost 240 wells (Manzella et al., 2019) through several hundred kilometers of pipeline networks having different geometries and degrees of interconnection. Continuous monitoring of the operating conditions (flow rate, pressure and temperature) at any position of such large-scale systems is very difficult to achieve, mainly because it would require a large amount of components capable of withstanding the harsh conditions that characterize the geothermal service. For this reason, some of those variables are continuously measured using on-line instruments while others are periodically sampled using portable devices. The lack of on-line measurements providing a complete overview of the steam pipeline network operations and the complex large-scale nature of these systems make difficult to manage them efficiently using an experience-based approach. Numerical modeling and simulation tools play an important role in responding to this challenge. For example, they allow to predict pressure or flow rate changes due to variations in the network configuration as a consequence of the opening or closing of valves. Therefore, each maneuver could be simulated before being applied, avoiding production losses and waste of time typically related with trial and error procedures. In addition, these tools allow for a thorough study of different options when the need to re-design a part of the steam gathering system arises, for instance, to integrate a new well. The numerical model can be used to simulate the candidate solutions and hence to compare performance and economics. Finally, a simulator provides an off-line virtual environment where technicians can effectively gain experience in operating steam pipeline networks.

Enel Green Power has constantly worked on setting up increasingly reliable numerical models for both design and simulation purposes. In the late 70’s the company pioneered the research on geothermal network simulation creating VAPSTAT-1 computer code (Marconcini and Neri, 1979) and simulating a six-wells steam transportation network in the Larderello geothermal field. A single-phase fluid flow simulator, evolution of VAPSTAT-1, was developed in the following years and used as a decision support tool in determining how to optimally integrate a new well to an existing steam gathering system in the Monteverdi geothermal area (Ciurli and Barelli, 2009).

The present paper deals with the ongoing numerical modeling of a steam pipeline network located in Tuscany traditional area using the commercial software Dymola®. In §2 a brief description of the network is provided with a particular focus on thermodynamic and chemical characteristics of the piped fluid, its main components and the geothermal power plants connected. §3 is devoted to introduce Modelica language, simulation environment Dymola® and the model created. In §4, some simulation results are showed and compared with real data for model validation. Then, a case study of interest is presented.

2. DESCRIPTION OF THE STEAM PIPELINE NETWORK

The traditional geothermal area of Tuscany hosts a steam-dominated geothermal system showing a geological structure characterized by the presence of shallow reservoirs within carbonate and anhydritic formations and deep reservoirs localized in the metamorphic basement. The network modeled has 37 production wells connected supplying fluid at different thermodynamic conditions and with peculiar chemical composition depending on the reservoir they belong to. PW_1÷4 production comes from a shallow carbonate reservoir RES_1 at 600÷800 m depth having a temperature of 270°C (Bertani et al., 2005) and a pressure of 1.1 MPa. They provide superheated steam with a non-condensable gas content of 4÷7 % by weight. PW_5÷12 belong to a reservoir RES_2 with a pressure of 2.5 MPa and temperature of 225÷275°C hosted in carbonate formations at a depth of 1300÷2500 m (Bertani et al., 2005). PW_6 and PW_9 produce superheated fluid while all the other wells provide wet steam; the non-condensable gas content ranges from 3 to 12 % by weight. PW_13÷37 produce from two deep reservoirs RES_3 and RES_4 at 2000÷3500 m depth whose fluid is characterized by a pressure of 4.5 MPa, a temperature of 300÷350°C (Bertani et al., 2005), a non-condensable gas content of 1÷10 % by weight and a high concentration of chloride (>100 ppm). In order to remove HCl and avoid corrosion both of casing and surface equipment, an alkaline aqueous solution at ambient temperature is injected into the fluid flow either into the wellbore or along a specifically designed manifold depending on the steam superheating. The resulting bi-phase fluid is passed through a vertical separator, located on the well pad, where the water enriched in chlorine is removed. The wet steam is finally conveyed to the gathering system while the liquid is sent to the water pipeline network and hence re-injected back into the reservoirs.

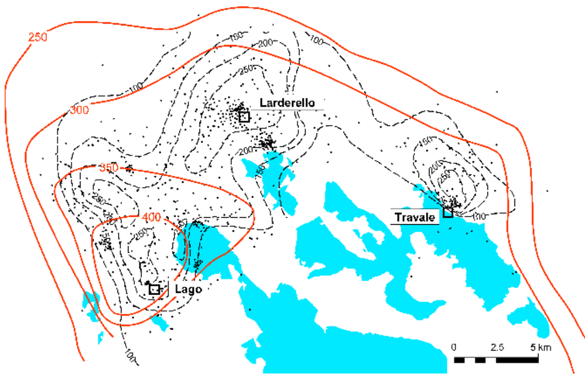

Figure 2: Temperature distribution in Tuscany traditional geothermal area. Outcrops of permeable formations are highlighted in blue while geothermal wells are represented with black dots. (Figure from Romagnoli et al., 2010)

The fluid from producing wells is transported to power plants through a network of over 35 km of welded steel pipes. The pipe nominal diameter varies a lot from one point to another of the network: it ranges broadly from 300 to 600 mm for pipes connecting one or more wells located in the same well pad to the main ducts, and from 600 to 800 mm for those collecting the total fluid through a power plant. The pipelines are thermally insulated with a layer of rock wool, having different thickness depending on the fluid temperature, covered by a properly shaped aluminum cladding sheet; drain pots and steam traps are present to collect and remove any condensate that could form. The pipe routes are complex due to frequent changes in elevation and the presence of several expansion loops necessary to handle pipelines thermal expansion. Zigzag and U-shape paths are commonly used depending mainly on the availability of area (Figure 3). In the zigzag configuration, thermal expansion is absorbed by changing the pipeline direction, while in the U-shape ones thermal movements are accommodated with sections of piping running perpendicularly. Steam gate valves are present at all connections of the network both to isolate long pipes into sectors for safety and maintenance reasons and to regulate the fluid distribution for an adequate steam supply to the power plants.

Figure 3: U-shaped and zigzag expansion loops.

Presently eight power units are installed: two 40 MWe and six 20 MWe dry-steam condensing groups for 200 MWe of total capacity. The incoming fluid through the power plant inlet duct, formed by steam and non-condensable gasses, is passed into a separation unit in order to definitely remove condensate and solid particles that may be present. Then it enters the turbine where, expanding through a series of alternating rotating and stationary blades, most of its enthalpy is converted into mechanical energy to rotate the turbine shaft. The turbine rotor in turn drives an alternator which transforms the mechanical energy into electrical energy. The fluid exits the turbine with moderate pressure and temperature, and enters a water-cooled direct contact condenser. Non-condensable gasses are removed from the condenser by means of a centrifugal compressor and sent to the AMIS treatment plant for mercury and hydrogen sulphide abatement (Baldacci et al., 2005). The condensate formed instead is pumped into mechanical draft wet type cooling towers, cooled down, and gathered in the tower basin. The cold water is then re-circulated to the condenser to be used as coolant for condensing the exhaust fluid, while the tower overflow is sent to the water pipeline network and re-injected back into the reservoirs.

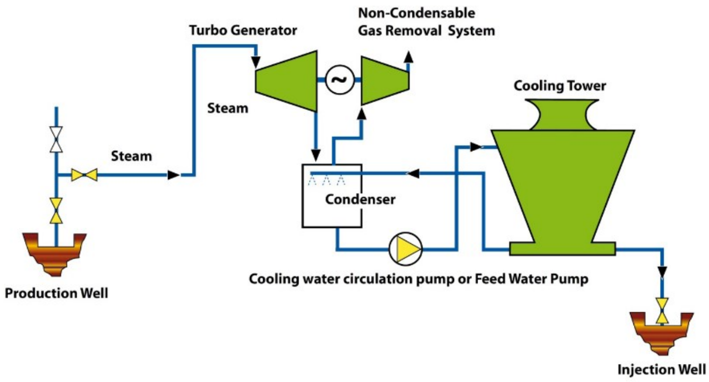

Figure 4: Schematic of a dry steam condensing geothermal power plant.

3. DESCRIPTION OF THE NUMERICAL MODEL

A steam pipeline network can be seen as a collection of interacting components (wells, pipes, valves, power units), belonging to different engineering fields. There were many attempt to model heterogeneous physical systems by interfacing different tools addressing a specific domain. However, the most efficient approach is to use those with multi-disciplinary modeling capability (Van Beck and Roda, 2000).

Modelica is an object-oriented language developed from the Modelica Association considered nowadays one of the most promising for continuous and discrete-event modeling of heterogeneous physical systems (Fritzon and Bonus, 2002). The basic design idea of modeling with Modelica is to break down physical systems into fundamental parts and describe each part, independently from the others, with a set of differential, algebraic and discrete equations with no need of assignment statements. Equations can be written directly into the complicated form and, once declared inputs and outputs, their solution sequence will be automatically determined by causality between variables. This results in a better reusability of the models created as they contain fewer information about the context in which they are used than those created with conventional block-diagram oriented language where input-output relationships are fixed (Fritzon and Bonus, 2002). Reuse of modeling knowledge is also supported by the presence of libraries where the models created can be stored and hence quickly re-employed in different projects by referencing them. Modelica Association develops and maintains together with the Modelica language also a standard library of Modelica models called Modelica Standard Library. This library is intended to prevent Modelica users from creating their own basic models for the most commonly needed components and simplify model exchange accordingly (Otter and Elmqvist, 2000). Modelica Standard Library includes also connector definitions, i.e. rigorously defined interfaces by which models transfer information each other. Therefore, complex physical systems can be quickly modeled in Modelica by connecting several ready-to-use components creating only those that do not exist using standard interfaces.

A Modelica model cannot be executed directly but requires a symbolic transformation algorithm to convert the set of equations describing the system into a form that can be easily integrated with a numerical method. Transformation algorithm and solvers are implemented into properly developed environments that are necessary for the convenient utilization of Modelica language. Dymola® is a commercial modeling and simulation environment based on Modelica, wholly owned by Dassault Systémes®. It has a graphical user interface to conveniently create models as a result of a graphical editing regardless of the related Modelica syntax which is hidden to the end-user. Dymola® implements a Modelica compiler allowing symbolic transformation of large systems of equations and also suitable for real time applications. Translated models can be simulated in Dymola® with several integration algorithms enabling the user to choose the most appropriate for the specific case.

3.1 Component models

The steam pipeline network numerical model described in the present paper was developed in Dymola® environment. Due to the large-scale nature of the network, it was required to balance the level of detail of the numerical model in order to run simulations with a reasonable speed of execution. Most of the implementation was done using Modelica Standard Library blocks, while a model for the dry-steam geothermal well was created as well as for the dry-steam condensing unit. In this section, custom blocks and the features of Modelica standard components that are relevant in the context of the present paper are presented. The interested reader is referred to Modelica Standard Library documentation for more details about standard components.

3.1.1 Dry steam geothermal well

The deliverability of a geothermal well is typically defined by the so-called characteristic curve that relates the mass flow rate discharged with the corresponding wellhead pressure. The curve is specific for each well and is routinely determined during production tests. The model is based on the following set of equations describing the fluid pressure behavior in formation (1) and in the borehole (2); combining these relationships and rearranging them the analytical expression of the well characteristic curve can be derived.

$$P_{res}^2 - P_{fl}^2 = \alpha G \tag{1}$$

$$P_{fl} - P_{wh} = \beta G^2 + \rho g h \tag{2}$$

P_{res} is the reservoir pressure, P_{fl} is the flowing pressure, P_{wh} is the wellhead pressure, α is a laminar (or Darcy) coefficient, β is a turbulent coefficient, G is the mass flow rate, ρ is the fluid average density into the well, g is the acceleration of gravity and h is the feed-zone vertical depth.

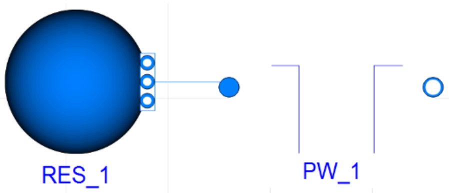

Figure 5: Dry steam geothermal well model.

The Modelica model developed is composed of two elements: a *FixedBoundary* block taken from Modelica Standard Library representing the reservoir and a custom block for the well (Figure 5). P_{res}, provided as an input to the *FixedBoundary* element, is determined from the shut-in pressure of both monitoring wells and production wells temporarily out of service. α, β and h are the input variables of the well block. The laminar coefficient derives from a curve fitting of the well operating data, the turbulent ones is evaluated on the base of the well technical profile and the feed-zone depth is determined from tests performed during or after drilling operations.

3.1.2 Dry steam condensing group

Similarly to geothermal well, even power unit performances can be described by a characteristic curve relating the mass flow rate with the inlet pressure. The model developed is based on a linear characteristic curve expressed by the following equation.

$$P_{T,in} = P_{cond} + kG \tag{3}$$

$P_{T,in}$ is the turbine inlet pressure, P_{cond} is the condenser operating pressure and k is the turbine flow coefficient (Ciurli and Barelli, 2009).

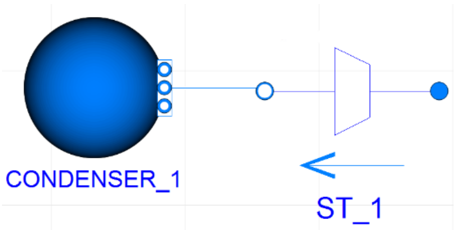

Figure 6: Dry-steam condensing group model.

The model, shown in Figure 6, consists of a *FixedBoundary* block representing the condenser and a custom block for the steam turbine. P_{cond} is continuously measured during normal operations and it is assigned as input to the condenser block. k is the only input variable required by the steam turbine block. It depends on the turbine configuration and it is derived from the steam turbine operating parameters.

3.1.3 Pipe

The pipeline network model was created connecting several *DynamicPipe* elements of the Modelica Standard Library. It is a component which describes the fluid pressure behavior in a straight pipe of a given geometry. *DetailedPipeFlow* pressure drop model was selected among the different alternatives implemented in the block whereas the pipe geometric characteristics (length, nominal diameter, roughness) were provided as inputs. At the present stage of development, the network is assumed as composed by straight pipes only and the pipe roughness used as an empirical coefficient to take into account of the actual pipeline routes in the pressure drop calculation. As in some cases the flow direction is not known a-priori, the reverse flowing option was enabled for all *DynamicPipe* elements, that is the fluid flow can occur in both pipe directions.

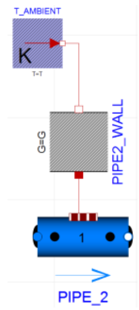

Figure 7: Pipe model.

Heat exchange between the pipeline and the surrounding environment was modeled by combining the pipe model with *ThermalConductor* and *FixedTemperature* blocks provided within Modelica Standard Library (Figure 7). *ThermalConductor* is a model for heat transport that requires as input the overall thermal conductance of pipe wall and insulation layers, which is therefore assumed as constant over the temperature range of interest. *FixedTemperature* instead defines the ambient temperature outside the pipeline as a boundary condition. This latter component allows also to fix the discharging temperature of each production well.

3.1.4 Valve

Modelica Standard Library element *ValveCompressible* was used for the gate valves present on the pipeline network. The model, developed according to the IEC 534/ISA S.75 standard for valve sizing, calculates the mass flow rate through the valve depending on the up and down stream fluid properties and the opening degree.

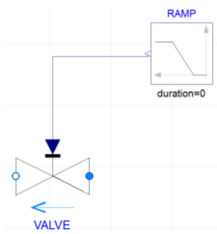

Figure 8: Valve model.

Each *ValveCompressible* was connected with the Modelica Standard Library component Ramp that allows to specify the desired ramp or step signal for opening or closing of the valve. As for *DynamicPipe* block, reverse flowing option was enabled even for this element.

3.2 Fluid thermodynamic properties

In order to determine the fluid properties, such as density or viscosity, under different thermodynamic conditions a proper set of equations of state must be implemented. The geothermal fluid provided by the production wells of the area is characterized by a non-condensable gas content ranging from 3 % to 12 % by weight composed mostly by carbon dioxide. Despite Modelica Standard Library contains several models for the evaluation of thermodynamic properties of different fluids, it lacks of formulations for water-carbon dioxide mixtures. For this reason, a proper thermodynamic library will be implemented in the future. In the present paper the working fluid was assumed to be composed only by water and its properties were calculated according to the IAPWS-IF97 formulation available within Modelica Standard Library.

IAPWS-IF97 was developed in 1997 by the International Association for the Properties of Water and Steam (IAPWS) to replace the previous IFC-67 used as a standard for power-plant calculations and other energy engineering applications since 60's (Wagner and Kretzschmar, 2000). The IAPWS Industrial Formulation 1997 covers a range of validity identified in a pressure-temperature chart by the following boundaries.

$$273.15\ \text{K} \leq T \leq 1073.15\ \text{K} \qquad P \leq 100\ \text{MPa}$$

$$1073.15\ \text{K} < T \leq 2273.15\ \text{K} \qquad P \leq 50\ \text{MPa}$$

The range is divided into five regions where different basic equations, showed in rectangular boxes in Figure 9, are used for thermodynamic calculations. Figure 9 includes further equations for regions 1, 2, and 4 called backward equations. In regions 1 and 2 they relate the fluid temperature with pressure and specific enthalpy or pressure and specific entropy, whereas in region 4 they express the dependence of saturation temperature from pressure. These equations allow to speed up the calculation of several properties of interest.

The present numerical model implements a IAPWS-IF97 formulation to determine the fluid thermodynamic properties as functions of pressure and specific enthalpy.

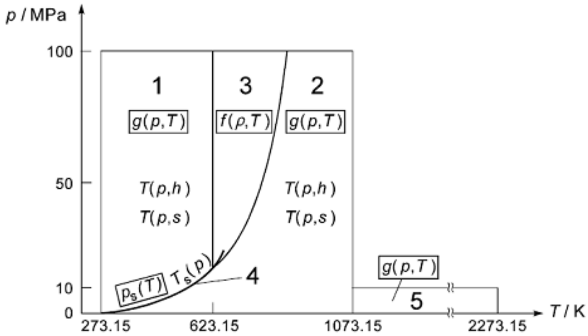

Figure 9: Regions and equations of IAPWS-IF97 (Figure from Wagner and Kretzschmar, 2000).

4. SIMULATION RESULTS

The present section is divided in two parts: the first focuses on model development and validation, while the second concerns with a case study of interest. In the first part, once recapped the main phases of the modelling process, simulation results related to the current configuration of the network, referred to as base-case scenario, are compared with real data. In the second part an example of application is presented where the model developed was used as a decision support tool in optimizing the steam pipeline network layout and operating parameters.

4.1 Model development and validation

The model development began by gathering from the company database the technical documentation related to the network, such as flow diagrams, pipe geometric attributes, thermal properties of insulating material, and valve characteristics. If changes are made to a given component, these documents are properly reviewed by the competent corporate functions and hence they contain the most updated design and construction information. The network flow diagram was faithfully reproduced in the Dymola® environment using the graphical user interface. The blocks presented in §3 were dragged and dropped from libraries into the working sheet and connected according to the schemes collected to form the simulation model. A tag consistent with those reported on the technical documentation was assigned to each component on the working sheet that is therefore uniquely identified. This facilitate handling the large amount of simulation results, updating the numerical model in case of changes to the network layout and the exchange of information between modelers and technicians of other corporate functions. The pipe attributes (length, nominal diameter) found in the technical documentation were specified for each *DynamicPipe* component as well as it was done for the valve blocks parameters. The valves opening degree were set according to the indications provided by on-site operators in order to reproduce the actual distribution of the fluid through the pipeline network. Afterwards, the modeling process continued by collecting from the company database the production history, the drilling report, and the well test results of the geothermal wells of interest. Production history includes mass flow rate, wellhead pressure, wellhead temperature and non-condensable gas content measurements performed by technicians with scheduled frequency on the fluid delivered by each well along all its operating life. In addition, it includes also the shut-in pressure measures of monitoring wells. The most recent wellhead temperature data were directly assigned as input to the related *FixedTemperature* elements. The input parameters for each well block instead were derived from the analysis of the whole dataset coupled with well profile and feed-zone vertical depth information contained within drilling reports and well test results. Primary data for building the model were also power unit operating conditions measurements from which the inputs of the related block were determined.

Once reproduced the network flow diagram in Dymola® working sheet and provided all the necessaries input variables, numerical simulations were run in order to define roughness and thermal conductance values of each pipe block that allow to obtain the best match of the actual field data referred to normal operations during a specific date. The DASSL integrator (Petzold, 1982), a general-purpose solver of implicit systems of differential/algebraic equations, was use to simulate the compiled model. In Figure 10 simulated variables are plotted with respect to the y-axis while the measured ones on the x-axis. The closer are dots to the 45 degrees line, the smaller is the difference between real and calculated values and the better the model represents the actual behavior of the physical system. A good alignment with the 45 degrees deviation can be observed for all the variables. Concerning power units data, inlet pressures have a maximum relative error of 4.3 % and an average relative error of 1.4 % (standard deviation 1.9); mass flow rates show similar maximum and average relative errors, 3.5 % and 1.1 % (standard deviation 1.3) in the order. As can be derived from the schematic of the network in Figure 12, all the power units, with the only exception of PU_4, are fed with wet steam coming from RES_2, RES_3 and RES_4 reservoirs. Figure 10 shows that the simulator tends to overestimate the inlet temperatures of these groups. The reason is that the thermodynamic library implemented does not consider the non-condensable gas content of the working fluid and, as a consequence, predicts a saturated temperature at the turbine inlet pressure that is higher than the actual. In particular, the maximum relative error was 4.1 % while the average ones 1.7 % (standard deviation 1.5).

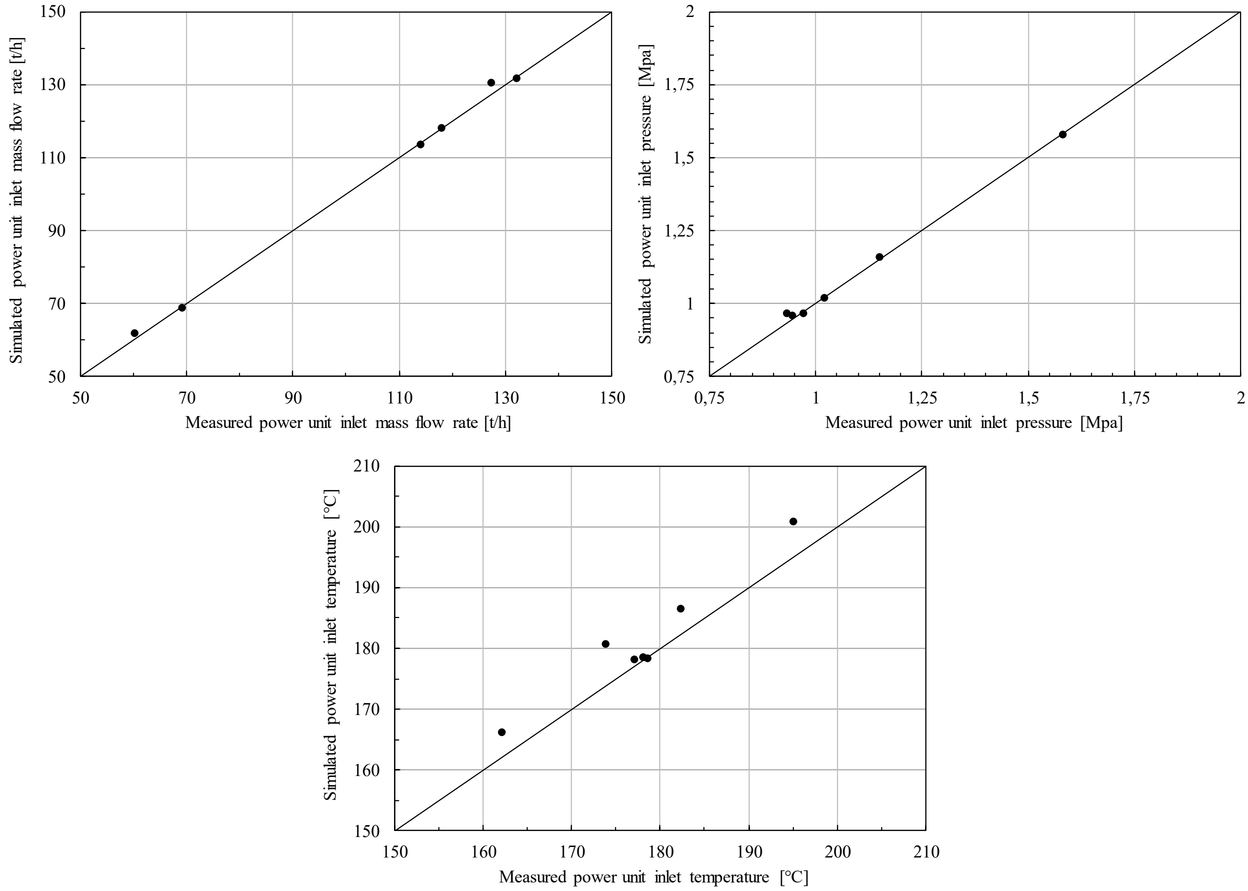

Figure 10: Comparison of measured data and simulation results – Power units.

Regarding wells data (Figure 11), wellhead pressures present a maximum relative error of 8.3 % that is smaller than mass flow rate ones, equals to 10.3 %. This is because production wells belonging to the low-pressure reservoir RES_1 operate in the left part of their characteristic curve where the mass flow rate discharged varies considerably with the wellhead pressure. Therefore, errors in the wellhead pressure calculation translate into bigger ones in the mass flow rate estimation. The opposite is for production wells belonging to the high-pressure reservoirs RES_3 and RES_4 that operate instead in the right part of the characteristic curve, where the mass flow rate discharged is almost constant with the wellhead pressure. As the most of the wells connected to the steam pipeline network modeled belongs to high-pressure reservoirs, the average error referred to wellhead pressures (3.2 %; standard deviation 2.3) is higher than that referred to mass flow rates (2.3 %; standard deviation 2.5).

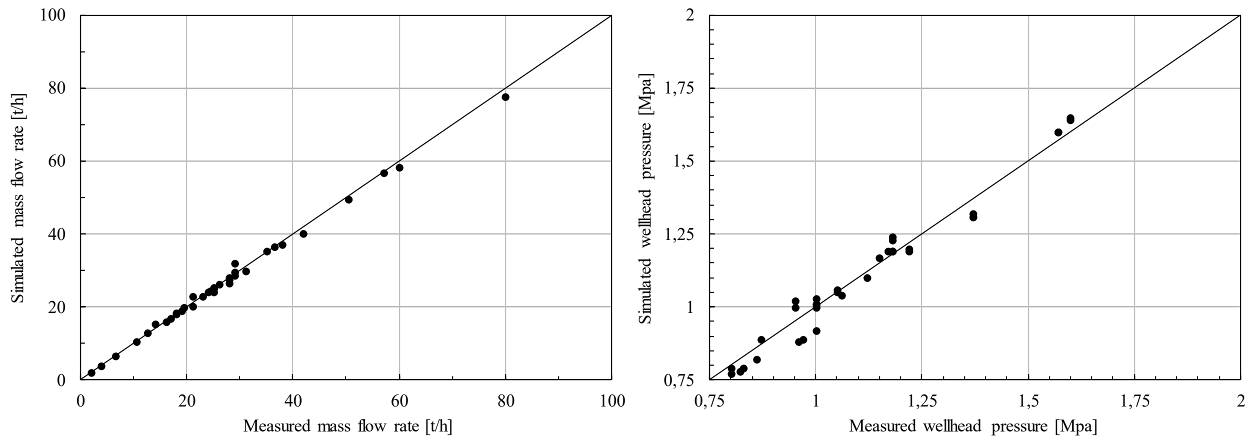

Figure 11: Comparison of measured data and simulation results – Production wells.

4.2 Case study

The modeled steam pipeline network is located in an intensively exploited zone of the geothermal field. The exploitation results in a natural decline of the system with a consequent progressive lowering of the total production. In spite of the activities carried out over the last years to contrast this phenomenon, such as the drilling of new production wells and the application of different water injection strategies, there is still not enough fluid to operate all the power units at their full capacity.

Once validated the numerical model, simulations were performed in order to assess whether there were any improvements that could be applied to optimize the steam pipeline network operating conditions and increase power generation. A preliminary analysis evidenced the need to focus on production wells belonging to low-pressure reservoir RES_1. In the base case configuration presented in Figure 12, PW_1÷4 produce at wellhead pressures close to their shut-in pressures, affecting negatively both steam pipeline network operability and performances. Lowering their discharging pressure allowed to operate these wells rightmost in the characteristic curve with an ensuing increase of the total fluid available and a higher operational flexibility in responding to pressure variations. To accomplish this end with limited plant modifications, it was identified a solution that concerns the switching of PW_1÷4 wells on PU_5, located within the same power plant of PU_4, and the change of PU_5 turbine configuration in order to obtain the desired wellhead pressures. The realization of this scenario required, besides the turbine modification, also the installation of two by-pass lines and four valves to divert the low-pressure fluid on PU_5 group and the high-pressure ones on the PU_4. These components were coherently included in the network flow diagram implemented in Dymola® and simulations were performed in order to define the new configuration of the network, the nominal operating point of each power unit connected and identify possible critical issues.

A schematics of the network arrangement developed is showed in Figure 13, while the simulation results for the base case and the present case study are shown in Table 1. Since PU_1 keeps on being isolated from the rest of the network, its operating conditions are the same in both scenarios. The dry steam produced by PW_1÷4, that fed PU_4 in base case, is transported to PU_5 through a dedicated low-pressure pipeline network. Therefore, PU_5 inlet conditions, that were saturated in the base case, becomes superheated in the case study, while PU_4 ones goes to saturation. In the new configuration, production wells belonging to shallow and deep reservoirs can be operated at different pressures with a positive effect on the generated power. For instance PW_15÷17, which belong to the high-pressure reservoir RES_3, produce more conveniently at higher discharging pressures than in the base case. Besides, PW_1÷4 wellhead pressures can be lowered so that these wells could supply the necessary amount of fluid to operate PU_5 group at its full capacity. Finally, diverting all production wells of the low-pressure reservoir RES_1 on the same group provides a high degree of flexibility in responding to resource change over the time.

The new network arrangement foreseen variations of the steam turbines configuration and, as a consequence, of the network operating pressures. In general, the wells affected by an increase of their discharging pressure with respect to the base case respond with a lower production, while the opposite was for those that experienced a decrease of the wellhead pressure. Simulation outcomes show that the realization of the new network configuration lead to a rise of the total fluid available of about 20 t/h corresponding, as a result of a rough estimation based on historical data, to an increment in the power generated of 2.5 MWe approximately. As showed in the PU_4 and PU_5 detail reported in Table 2, PW_1÷4 contribute significantly to the increment of the total production. This is because they operate in the left part of the characteristic curve in the base case; therefore, lowering their wellhead pressures resulted in a considerably higher mass flow rate supplied. Conversely, the wells that produce from the high-pressure reservoirs RES_3 and RES_4, such as PW_15÷17, work in the right part of the characteristic curve in the base case. Thus, slight changes of the wellhead pressure (with respect to their shut-in pressure) do not translate in a sensible variation of production for them.

	BASE CASE			**CASE STUDY**		
Power unit	**Mass flow rate [t/h]**	**Inlet pressure [MPa]**	**Inlet temperature [°C]**	**Mass flow rate [t/h]**	**Inlet pressure [MPa]**	**Inlet temperature [°C]**
PU_1	62.1	0.72	166.2	62.1	0.72	166.2
PU_2	130.6	0.97	178,7	128.2	0.92	176.4
PU_3	113.7	1.02	180.9	105.8	0.95	177.8
PU_4	198.1	0.73	178.5	230.2	0.93	176.9
PU_5	118.2	1.16	186.6	131.4	0.62	185.6
PU_6	172.2	0.96	178.3	168.7	0.77	169.0
PU_7	68.9	0.97	178.7	63.6	0.79	170.0
PU_8	132.0	1.58	200.9	126.4	1.51	198.8
TOTAL	**995.8**	-		**1016.4**	-	

Table 1: Simulation results - power units.

	BASE CASE		**CASE STUDY**	
Well	**Mass flow rate [t/h]**	**Wellhead Pressure [MPa]**	**Mass flow rate [t/h]**	**Wellhead Pressure [MPa]**
PW_1	22.8	0.77	27.6	0.68
PW_2	32.0	0.79	37.9	0.72
PW_3	40.1	0.79	47.5	0.72
PW_4	15.3	0.78	18.4	0.70
PW_15	18.9	0.92	18.8	0.98
PW_16	58.4	0.89	57.1	1.10
PW_17	10.6	0.88	10.4	1.08
TOTAL	**198.1**	-	**217.7**	-

Table 2: Simulation results - PU_4 and PU_5 detail.

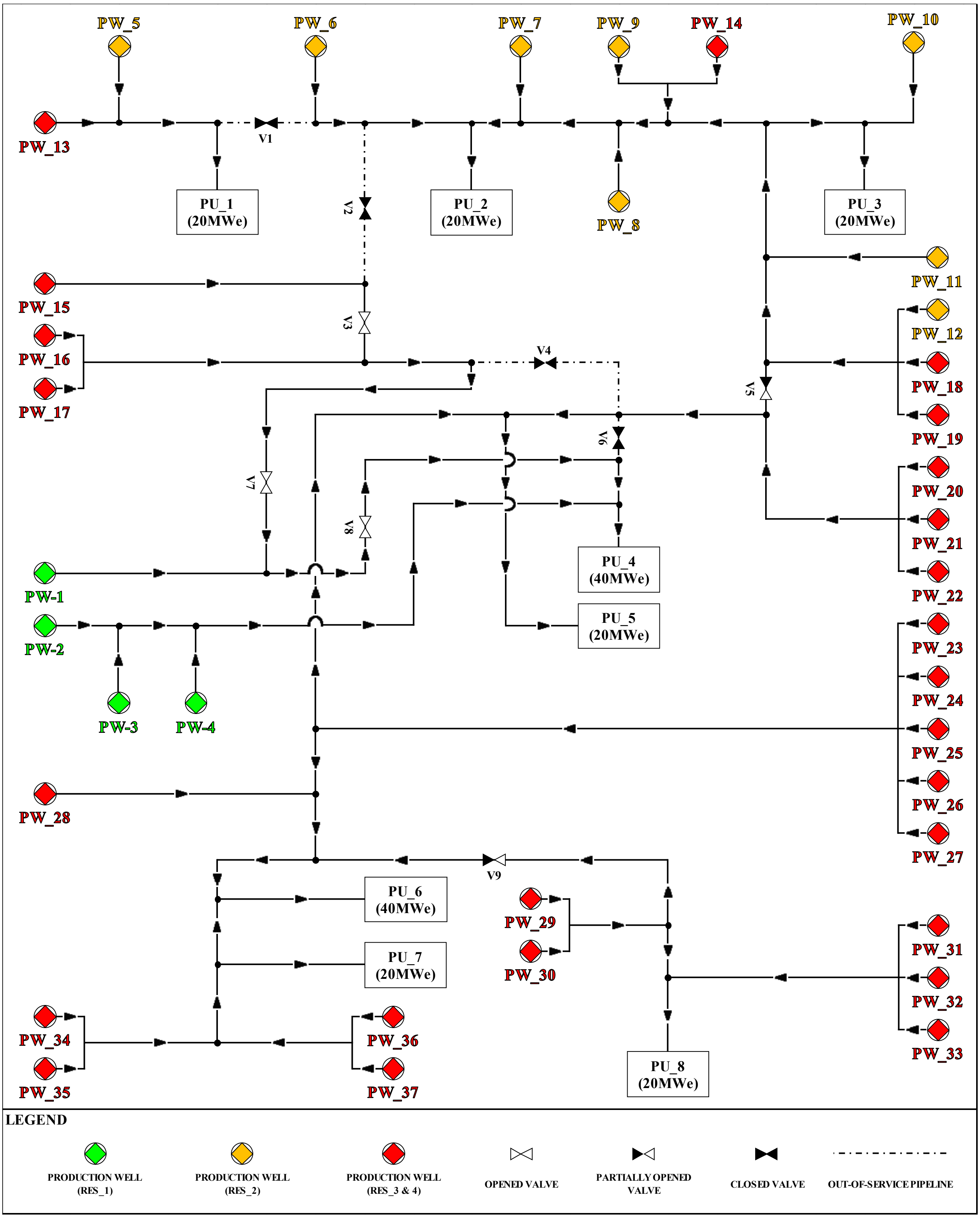

Figure 12: Schematics of the steam pipeline network - base case.

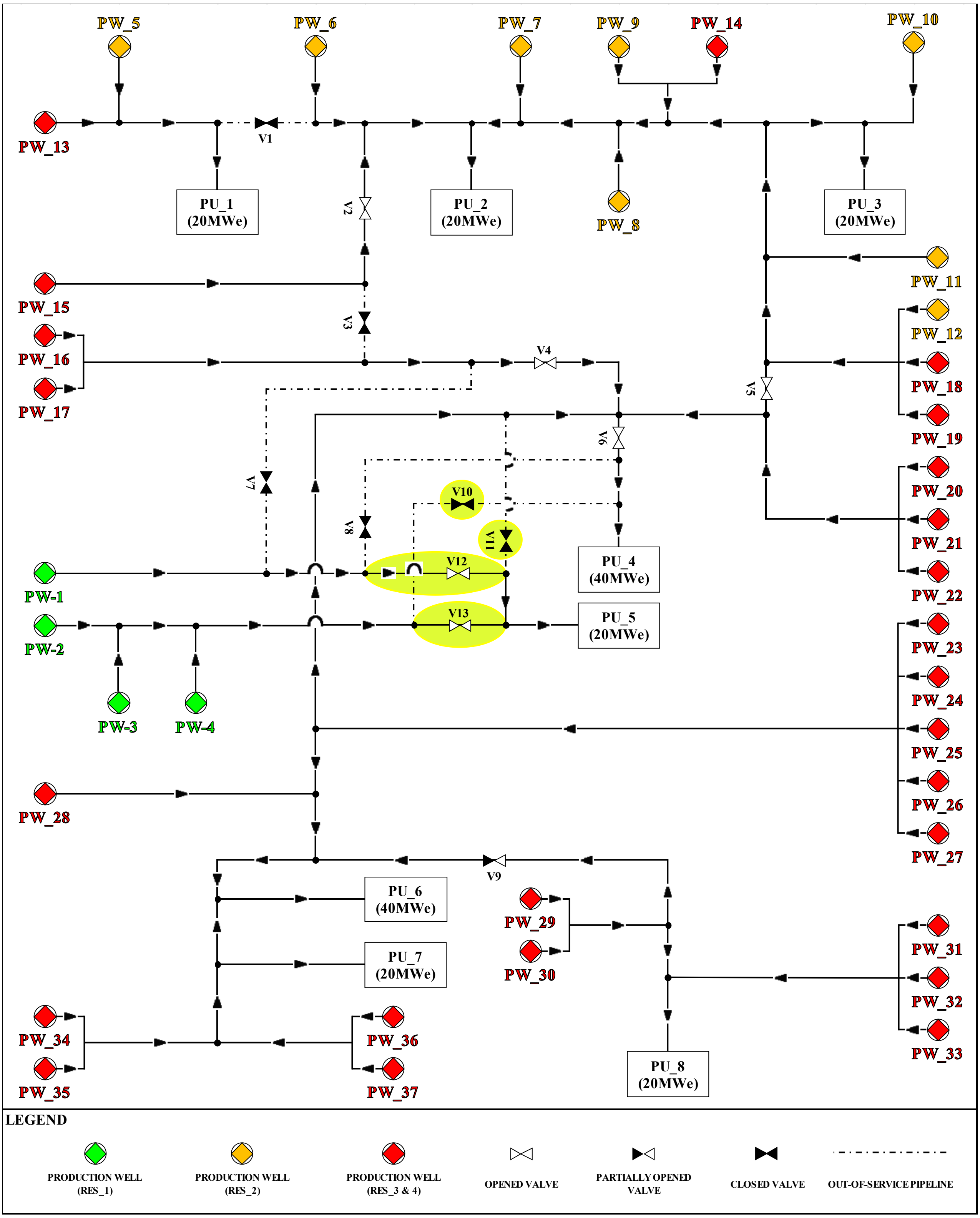

Figure 13: Schematics of the steam pipeline network - case study. Additional parts with respect to the base case scenario are circled in yellow.

5. CONCLUSIONS

The paper focused on the on-going numerical modeling of a steam transportation system located in Tuscany traditional area. The work was motivated by the need to have a state-of-art tool for evaluating the performances of complex pipeline networks under different operating conditions. The network flow diagram was reproduced in Dymola®, a simulation environment based on Modelica scripting language, according to the relative technical documentation collected from the company database. The model was composed by blocks included within Modelica Standard Library and two elements specifically created: the dry-steam geothermal well and the dry-steam condensing group. Simulations were performed to determine the values of pipes roughness and thermal conductance that allow to obtain the best match of the real data. The final data matching was considered satisfactory as the maximum relative deviation between calculated and measured variables was of about 10%. The main features of the numerical model developed were presented in a case study where it allowed to define a new network configuration that could led to an increase of about 2.5 MWe in the generated power.

The results show that, at the current stage of development, the model can replace the former in-house computer code to support the operation in maximizing the power generation by means of a proper distribution of the steam flows or in verifying a-priori the effects of maneuvers on the steam pipeline network. However, further improvements as well as a more extended validation are necessaries to increase the model reliability and widen its areas of application. Future works will be devoted towards the implementation of a proper fluid model for water- carbon dioxide mixtures to refine the prediction of the fluid thermodynamic properties. Moreover, it will be possible to calculate the non-condensable gas content in the group inlet flow rate and hence to estimate the gas-extraction system load. Next steps will concern also modification of custom blocks. In particular, the reservoir pressure, currently provided as a constant input to the dry-steam geothermal well element, will be expressed with a time dependent function derived from the analysis of the actual field data. Modelling the reservoir response to production over time will allow to make long term predictions of the steam pipeline network performances. Finally, a parametrization of the steam turbine performance characteristics provided by suppliers will be integrated within the dry-steam condensing unit block in order to better evaluate the power generated by each unit for various scenarios.

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