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Optimization of steam power systems in industrial parks considering the distributed heat supply and auxiliary steam turbines

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ABSTRACT

In the steam power system for the centralized heat supply in an industrial park, heat demands of all consumers are satisfied by the energy station, leading to the high steam delivery costs caused by the several distant enterprises. Additionally, the number of steam levels is limited due to the trade-off between distance-related costs and heat cascaded utilization, thus some consumers are supplied with heat at higher temperature than that of required, resulting in the low energy efficiency. To deal with the above problems, this work proposes an optimization model for steam power systems (SPSs) in industrial parks, which incorporates the distributed heat supply and auxiliary steam turbines (ASTs). Field erected boilers (FEBs) can independently supply heat to consumers, thereby avoiding the excessive pipeline costs. ASTs are used for the re-depressurization of steam received by consumers, which can increase the electricity generation capacity and improve the temperature matching of heat supply and demand. A mathematical model is established for the problem, in which the influence of different numbers of steam levels is considered, and the SPSs are optimized by the objective function of minimizing the total annual cost (*TAC*). A case study illustrates that the optimal number of steam levels, and the selective installation of FEBs and ASTs for consumers, can effectively reduce the cost of pipeline network, increase the income of electricity generation, and minimize the *TAC* of the system.

Keywords: Steam power systems, Steam turbines, Distributed heat supply

1. INTRODUCTION

The optimization of steam power systems (SPSs) has been extensively studied since the 1980s. In previous studies, SPSs of individual plants were optimized mainly in terms of the equipment structure and operating conditions for the minimum total costs. Papoulias and Grossmann [1] were the first to adopt mathematical programming method to optimize stream flowrates and sizes of units in SPSs. The equipment efficiency and the steam physical properties were given as parameters in their work. Bruno et al. [2] used second order polynomial correlations to calculate steam physical properties, and added the constraints related to steam physical properties in the model. Aguilar et al. [3] developed the equipment models, so that the variations in equipment efficiency were described. Sun et al. [4] noted the unsaturated steam conditions and obtained more realistic energy targets. Recently, Jiménez-Romero et al. [5] were the first to consider the effects of different numbers of steam levels in SPSs. However, in their study, the spatial scale of the SPSs was still limited to a single plant, thus the distance-related costs were neglected. At the spatial scale of industrial parks, there is a trade-off between energy cascaded utilization and distance-related costs in SPSs. As a remedy, we previously proposed a distributed steam turbine system model for optimizing the SPSs in industrial parks [6], aiming to balance the energy cascaded utilization and distance-related costs. Nevertheless, in Ref. [6], all consumers were supplied by a centralized energy station, leading to the high steam delivery costs caused by the several distant enterprises. Therefore, based on our previous research, this work provides consumers with the option of distributed heat supply in an effort to further reduce the distance-related costs and the total cost of the system.

2. PROBLEM STATEMENT

In an industrial park, enterprises and the energy station have been built at fixed locations. Enterprises are the heat consumers with different required temperatures and heat loads, and are denoted as i, $i \in I$, $I = \{I_1, I_2, ..., I_m\}$. The energy station supplies heat to enterprises using steam as the medium. In the energy station, very high pressure steam (VHPS) is produced in a large package boiler (LPB) with fuel consumed, and then is depressurized through main steam turbines (MSTs) into lower-pressure steam for heat supply, while electricity is generated, so that energy is utilized in cascade. Steam levels are denoted as s, $s \in S$, $S = \{S_1, S_2, ..., S_n\}$. Nonetheless, extremely high cost of the pipeline network is incurred when each required temperature is corresponded with a level of steam. Therefore, the number of steam levels is limited, and some consumers are supplied with heat at higher temperature than that is required. In this situation, auxiliary steam turbines (ASTs) are selectively installed for consumers, by which the received steam is re-depressurized, thereby increasing the electricity generation capacity. In addition, each consumer can choose to install a field erected boiler (FEB) for the distributed heat supply, so that the cost of steam pipeline network (SPN) is reduced. In the SPS, the costs include the capital cost of LPB ($C^{LPB,cap}$), the cost of fuel consumed by LPB ($C^{LPB,fuel}$), the cost of FEBs (C^{FEB}), the cost of steam turbines (C^{turb}), and the cost of SPN (C^{pipe}), while the income from electricity generation (I^{elec}) is obtained. In this study, the mathematical model is established and solved to determine the optimal number of steam levels, the operating conditions (such as saturation temperature and mass flow rate) and supply scheme of each steam level, and the configuration of FEBs and ASTs, aiming to design the SPS with the minimum total annual cost (TAC). The objective function is expressed by Eq. (1). The superstructure for the SPSs is expressed in Figure 1.

$$min\{TAC = C^{LPB,cap} + C^{LPB,fuel} + C^{FEB} + C^{turb} + C^{pipe} - I^{elec}\} \tag{1}$$

3. MODEL FORMULATION

3.1. Centralized steam production model

The pressure and temperature of VHPS are set as 4.5 MPa and 400 °C, respectively. The corresponding saturation temperature ($T^{VHPS,sat}$) and specific enthalpy (h^{VHPS}) are 257.4 °C and 3207 kJ.kg^{-1}, respectively. The physical properties of steam levels are calculated by fitting formulas Eqs. (2)-(5), with saturation temperature of steam levels $T_s^{MST,sat}$ as the independent variable.

$$h_s^{l,MST,sat} = 4.431 \cdot T_s^{MST,sat} - 29.89 \tag{2}$$

$$\Delta h_s^{is,MST} = -4.876 \cdot T_s^{MST,sat} + 1251 \tag{3}$$

$$\rho_s^v = 0.0005078 \cdot \left(T_s^{MST,sat}\right)^2 - 0.1053 \cdot T_s^{MST,sat} + 6.148 \tag{4}$$

$$\rho_s^l = -1.053 \cdot T_s^{MST,sat} + 1071 \tag{5}$$

where $h_s^{v,MST,sat}$ and $h_s^{l,MST,sat}$ are the specific enthalpies of saturated vapor and liquid of steam level s, respectively. $\Delta h_s^{is,MST}$ is the specific isentropic enthalpy difference of steam across the MST. ρ_s^v and ρ_s^l are the densities of vapor and condensate of steam level s.

The performance of MSTs is formulated by the

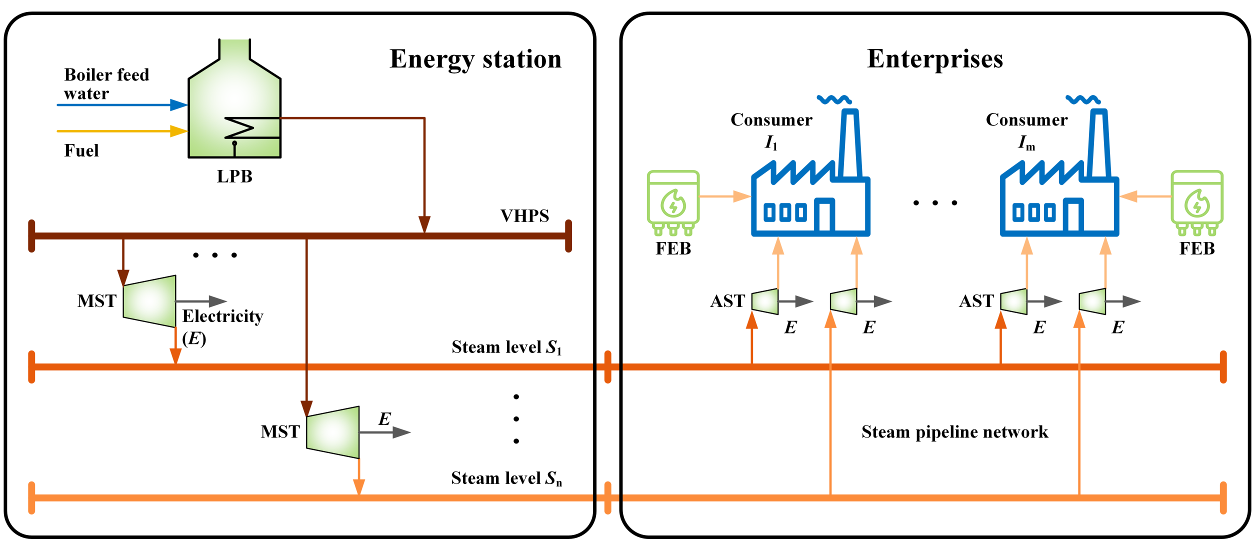

Figure 1: Superstructure of SPSs in industrial parks with FEBs and ASTs

model developed by Aguilar et al. [3], as expressed by Eqs. (6)-(8).

$$W_s^{MST} = \frac{m_s^{level} \cdot \Delta h_s^{is,MST} - [a_0 + a_1 \cdot (T^{VHPS} - T_s^{MST,sat})]}{a_2 + a_3 \cdot (T^{VHPS} - T_s^{MST,sat})} \tag{6}$$

$$h_s^{v,MST,out} = \frac{m_s^{level} \cdot h^{VHPS} - W_s^{MST}}{m_s^{level}} \tag{7}$$

$$h_s^{HV,MST} = h_s^{v,MST,out} - h_s^{l,MST,sat} \tag{8}$$

where W_s^{MST} is the shaft work of the MST for steam level *s*. a_0, a_1, a_2 and a_3 are the parameters. $h_s^{v,MST,out}$ and $h_s^{HV,MST}$ are the specific enthalpy and specific heat value of steam out from the MST, respectively.

The mass balance of steam levels is represented by Eq. (9).

$$m^{VHPS} = \sum_s m_s^{level} \tag{9}$$

3.2. Centralized steam supply model

In this work, the steam pipeline network is simply formulated. Consumers are divided into four directions, and are connected to the energy station by main and branch pipelines. Directions are denoted as *d*, $d \in D$, D = {East, West, North, South}. Consumers in each direction are denoted as *j*, $j \in J$, $J = \{J_1, J_2, ..., J_k\}$. The lengths of main pipeline segments $L_{d,j}^{main,seg}$ is calculated by Eq. (10) and Eq. (11), and the lengths of branch pipeline segments $L_{d,j}^{bran}$ is calculated by Eq. (12).

$$L_{d,j}^{main} = \begin{cases} X_i, \ d = \text{East}(\ |X_i| \geq |Y_i|, X_i > 0) \\ |X_i|, \ d = \text{West}(\ |X_i| \geq |Y_i|, X_i < 0) \\ Y_i, \ d = \text{North}(\ |X_i| < |Y_i|, Y_i > 0) \\ |Y_i|, \ d = \text{South}(\ |X_i| < |Y_i|, Y_i < 0) \end{cases} \tag{10}$$

$$L_{d,j}^{main,seg} = \begin{cases} L_{d,j}^{main} & (j = J_1) \\ L_{d,j}^{main} - L_{d,j-1}^{main} & (j \neq J_1) \end{cases} \tag{11}$$

$$L_{d,j}^{bran} = \begin{cases} |Y_i|, \ d = \text{East} \\ |Y_i|, \ d = \text{West} \\ |X_i|, \ d = \text{North} \\ |X_i|, \ d = \text{South} \end{cases} \tag{12}$$

where $L_{d,j}^{main}$ is the distance of consumer *j* in direction *d* from the energy station in the main direction. X_i, Y_i are the coordinates of consumer *i* while the location of the energy station is set as the original coordinate.

The binary variable $y_{s,d,j}^{sup}$ is used to determine the supply scheme of steam levels, as expressed by the Big-M constraint Eq. (13).

$$m_{s,d,j}^{sup} \leq y_{s,d,j}^{sup} \cdot M^{sup,max} \tag{13}$$

where $m_{s,d,j}^{sup}$ is the mass flow rate of steam level *s* supplied to consumer *j* in direction *d*. Parameter $M^{sup,max}$ is the upper bound of $m_{s,d,j}^{sup}$.

The temperature constraint of steam supply is represented by Eq. (14).

$$T_s^{MST,sat} \geq y_{s,d,j}^{sup} \cdot T_{d,j}^{need} \tag{14}$$

where $T_{d,j}^{need}$ is the required temperature of each heat consumer.

The mass balance of steam in the pipeline network is formulated by Eqs. (15)-(17).

$$m_s^{level} = \sum_d m_{s,d}^{dire} \tag{15}$$

$$m_{s,d}^{dire} = \sum_j m_{s,d,j}^{sup} \tag{16}$$

$$m_{s,d,j}^{main,seg} = \begin{cases} m_{s,d}^{dire} & (j = J_1) \\ m_{s,d,j-1}^{main,seg} - m_{s,d,j-1}^{sup} & (j \neq J_1) \end{cases} \tag{17}$$

where $m_{s,d,j}^{sup}$ is the mass flow rate of steam level *s* supplied to direction *d*. $m_{s,d,j}^{main,seg}$ is the mass flow rate of steam in each main pipeline segment.

The inner diameters of steam main and branch pipeline segments ($D_{s,d,j}^{in,v,main,seg}$ and $D_{s,d,j}^{in,v,bran}$) are calculated by Eq. (18) and Eq. (19), respectively. The inner diameters of condensate main and branch pipeline segments ($D_{s,d,j}^{in,l,main,seg}$ and $D_{s,d,j}^{in,l,bran}$) are calculated by Eq. (20) and Eq. (21), respectively. The above inner diameters of pipelines are used to calculate the capital cost of the pipeline network C^{pipe}.

$$D_{s,d,j}^{in,v,main,seg} = \sqrt{\frac{4 \cdot m_{s,d,j}^{main,seg}}{\pi \cdot u^v \cdot \rho_s^v}} \tag{18}$$

$$D_{s,d,j}^{in,v,bran} = \sqrt{\frac{4 \cdot m_{s,d,j}^{sup}}{\pi \cdot u^v \cdot \rho_s^v}} \tag{19}$$

$$D_{s,d,j}^{in,l,main,seg} = \sqrt{\frac{4 \cdot m_{s,d,j}^{main,seg}}{\pi \cdot u^l \cdot \rho_s^l}} \tag{20}$$

$$D_{s,d,j}^{in,l,bran} = \sqrt{\frac{4 \cdot m_{s,d,j}^{sup}}{\pi \cdot u^l \cdot \rho_s^l}} \tag{21}$$

3.3. Consumer side model

The conditions of steam received by each consumer, including the saturation temperature $T_{d,j}^{rece}$, the mass flow rate $m_{d,j}^{rece}$, the specific enthalpy $h_{d,j}^{v,rece}$, the specific heat value $h_{d,j}^{HV,rece}$, are calculated by Eqs. (22)-(25).

$$T_{d,j}^{rece} = \sum_s \left(y_{s,d,j}^{sup} \cdot T_s^{MST,sat}\right) \tag{22}$$

$$m_{d,j}^{rece} = \sum_s \left(y_{s,d,j}^{sup} \cdot m_{s,d,j}^{sup}\right) \tag{23}$$

$$h_{d,j}^{v,rece} = \sum_s \left(y_{s,d,j}^{sup} \cdot h_s^{v,MST,out}\right) \tag{24}$$

$$h_{d,j}^{HV,rece} = \sum_s \left(y_{s,d,j}^{sup} \cdot h_s^{HV,MST}\right) \tag{25}$$

The existence of AST for each consumer is determined by the binary variable $z_{d,j}^{AST}$, and it is related to the saturation temperature drop $\Delta T_{d,j}^{sat,AST}$, as expressed by Eq. (26).

$$\Delta T_{d,j}^{sat,AST} \leq z_{d,j}^{AST} \cdot \Delta T^{sat,AST,max} \quad (26)$$

where parameter $\Delta T^{sat,AST,max}$ is the upper bound of $\Delta T_{d,j}^{sat,AST}$.

The performance of ASTs is formulated by Eqs. (27)-(31).

$$\Delta h_{d,j}^{is,AST} = \frac{\Delta T_{d,j}^{sat,AST}}{1854-1931 \cdot h_{d,j}^{HV,rece}} \quad (27)$$

$$W_{d,j}^{AST} = \frac{m_{d,j}^{rece} \cdot \Delta h_{d,j}^{is,AST} - \left(z_{d,j}^{AST} \cdot a_0 + a_1 \cdot \Delta T_{d,j}^{sat,AST}\right)}{a_2 + a_3 \cdot \Delta T_{d,j}^{sat,AST}} \quad (28)$$

$$h_{d,j}^{v,AST,out} = \frac{m_{d,j}^{rece} \cdot h_{d,j}^{v,rece} - W_{d,j}^{AST}}{m_{d,j}^{rece}} \quad (29)$$

$$h_{d,j}^{l,AST,sat} = 4.431 \cdot \left(T_{d,j}^{rece} - \Delta T_{d,j}^{sat,AST}\right) - 29.89 \quad (30)$$

$$h_{d,j}^{HV,AST} = h_{d,j}^{v,AST,out} - h_{d,j}^{l,AST,sat} \quad (31)$$

where $\Delta h_{d,j}^{is,AST}$ is the specific isentropic enthalpy difference of steam across the AST, and it is calculated by Singh's model [7]. $W_{d,j}^{AST}$ is the shaft work of the AST. $h_{d,j}^{v,AST,out}$ and $h_{d,j}^{HV,AST}$ are the specific enthalpy and specific heat value of steam out from the AST, respectively. $h_{d,j}^{l,AST,sat}$ is the specific enthalpy of saturated liquid of steam out from the AST.

The existence of FEB for each consumer is determined by the binary variable $z_{d,j}^{FEB}$. The relations among the centralized steam supply, AST, and FEB for each consumer are represented by Eq. (32) and Eq. (33).

In this work, it is assumed that the FEBs produce saturated steam at the required temperature of consumers, thus no electricity is generated at the same time. The saturation temperature of steam and the heat load actually used by each consumer ($T_{d,j}^{use}$ and $Q_{d,j}^{use}$) are expressed by Eq. (34) and Eq. (35), respectively. The former is constrained by Eq. (36), and the latter satisfies the energy balance, as expressed by Eq. (37).

$$\sum_s y_{s,d,j}^{sup} + z_{d,j}^{FEB} = 1 \quad (32)$$

$$z_{d,j}^{AST} \leq \sum_s y_{s,d,j}^{sup} \quad (33)$$

$$T_{d,j}^{use} = \left(T_{d,j}^{rece} - \Delta T_{d,j}^{sat,AST}\right) + z_{d,j}^{FEB} \cdot T_{d,j}^{need} \quad (34)$$

$$Q_{d,j}^{use} = m_{d,j}^{rece} \cdot h_{d,j}^{HV,AST} + z_{d,j}^{FEB} \cdot Q_{d,j}^{need} \quad (35)$$

$$T_{d,j}^{use} \geq T_{d,j}^{need} \quad (36)$$

$$Q_{d,j}^{use} = Q_{d,j}^{need} \quad (37)$$

where $Q_{d,j}^{need}$ is the required heat load of each heat consumer.

3.4. Objective function calculation

The economic terms $C^{LPB,cap}$, $C^{LPB,fuel}$, C^{FEB}, and C^{turb} in Eq. (1) are calculated by the formulas presented by Bruno et al. [2]. C^{pipe} and I^{elec} are calculated according to the methods in Ref. [8] and Ref. [9], respectively. The above calculations are not shown in detail here.

In this mathematical programming model, there are non-linear constraints for the steam physical properties, the equipment performance, and the energy balance. Furthermore, binary variables are used for the steam supply selectivity and the existence of equipment. Therefore, the model is formulated as a mixed-integer nonlinear programming (MINLP) model.

4. CASE STUDY

4.1. Data

As shown in Table 1, this case includes fourteen consumers. Different numbers of steam levels (*n*) are considered, ranging from one to five.

4.2. Model solution and results

The model is solved by a two-layer algorithm to deal with the solution difficulty, as shown in Figure 2. In the outer layer, the particle swarm optimization (PSO) algorithm transforms the variable $T_s^{MST,sat}$ into a parameter, and assigns it to the inner MINLP model. Once the saturation temperature of each steam level is determined, the supply selectivity of some consumers is eliminated due to the temperature constraint Eq. (14). Therefore, the feasible region is reduced and the inner model is much easier to be solved. In this work, the inner MINLP model is solved using Gurobi 11.0.1 as the solver.

Table 1: Data of consumers.

i	X_i (m)	Y_i (m)	T_i^{need} (°C)	Q_i^{need} (MW)
I_1	850	250	180	4.3
I_2	1450	400	125	4.8
I_3	1700	-650	135	3.1
I_4	1900	550	200	5.2
I_5	-600	500	160	3.4
I_6	-900	-150	175	2.9
I_7	-1500	300	190	4.0
I_8	-1800	-800	200	6.0
I_9	-250	700	175	4.2
I_{10}	650	1200	140	5.6
I_{11}	650	1200	225	2.3
I_{12}	-500	1700	240	5.7
I_{13}	950	-1300	210	4.1
I_{14}	-550	-1650	150	6.5

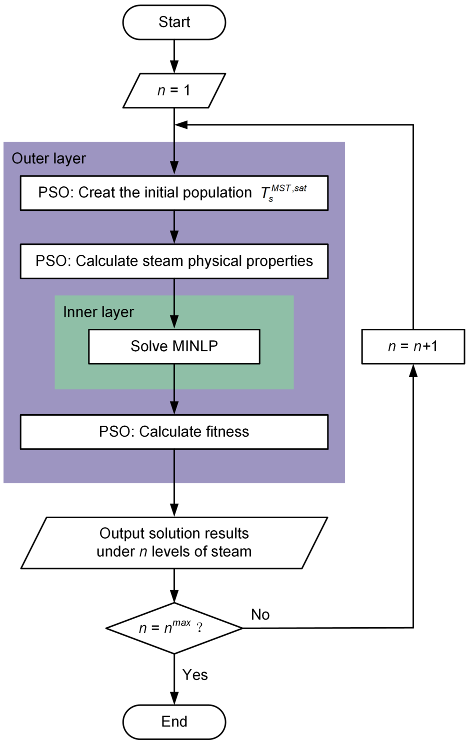

Figure 2. Solution algorithm.

The economic performance of the SPS under different numbers of steam levels is shown in Figure 3. It is indicated that the *TAC* of the SPS is minimized when the number of steam levels is two. The corresponding optimal scheme is presented in Figure 4.

4.3. Discussion

Figure 3 illustrates that among the different numbers of steam levels, the scheme with two steam levels has the second-lowest $C^{LPB,fuel}$, the second-lowest C^{pipe}, and the third-highest I^{elec}. The economic items of the system are well balanced, thus the lowest *TAC* is achieved. In this case, three consumers (J3, J4 in the North direction, and J1 in the South direction) require heat at temperatures higher than the saturation temperature of the two steam levels. Their required temperatures are 225 °C, 240 °C, and 210 °C, respectively. Therefore, FEBs are needed by them for distributed heat supply. As a consequence, the total length of the SPN decreases, thus C^{pipe} is reduced. On the other hand, the configuration of FEBs for the three consumers with high required temperature also allows the lower outlet saturation temperature of MSTs in the energy station, leading to the rise of the isentropic enthalpy change of MSTs. Therefore, a substantial electricity generation capacity is obtained, despite the reduction in the mass flow of VHPS. Besides, the combined electricity generation capacity of the three ASTs accounts for 8.5% of the total electricity generation capacity, also contributing to the reduction of *TAC*.

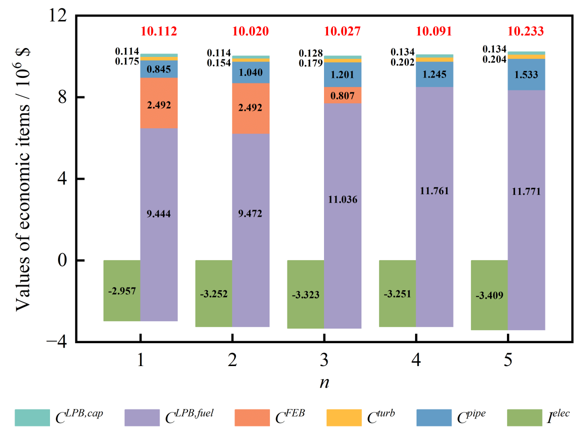

Figure 3. Economic results of the SPS.

5. CONCLUSIONS

An optimization model including the distributed heat supply and ASTs has been established for the SPSs in industrial parks. A case study demonstrates that the economic items of the SPSs vary with the number of steam levels. In this case, the optimal number of steam levels is two. With the arrangement of three FEBs and three ASTs, C^{pipe} decreases and I^{elec} increases, ultimately leading to the optimal design of the SPS with the minimum *TAC*.

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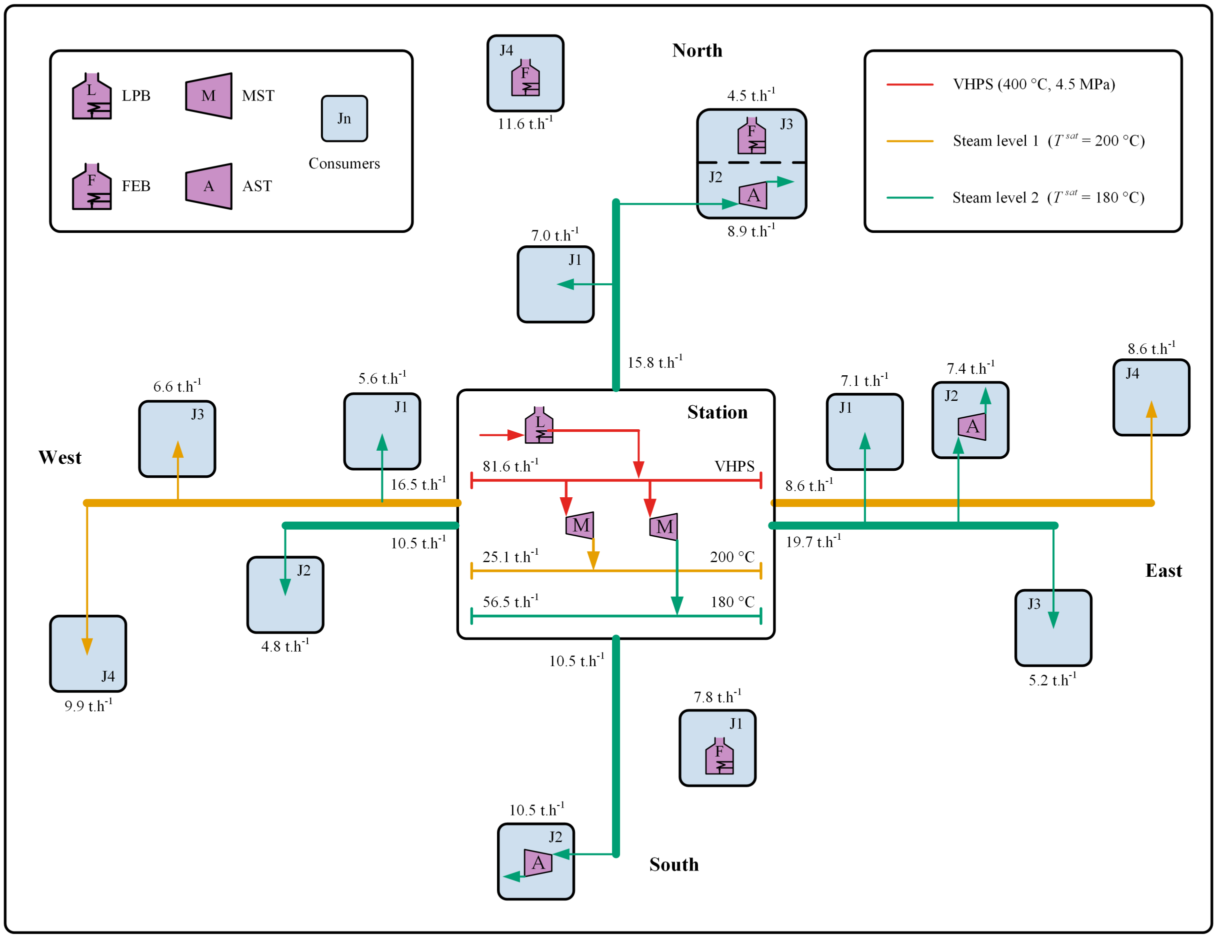

Figure 4: The optimal scheme.

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