TECHNO-ECONOMIC OPTIMIZATION OF CONFIGURATION AND CAPACITY OF A POLYGENERATION SYSTEM FOR THE ENERGY DEMANDS OF A PUBLIC SWIMMING POOL BUILDING

by

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A polygeneration system is an energy system capable of providing multiple energy outputs to meet local demands, by application of high process integration. In this paper, optimal configuration and capacity of a polygeneration system for an indoor swimming pool building is determined by application of a method based on TRNSYS simulation and GenOpt optimization software. Based on the applicability, a superstructure of the polygeneration system is integrated, consisting of the following polygeneration modules: an internal combustion engine cogeneration module, a vapor compression chiller, and adsorption chiller, a ground source heat pump, flat plate solar thermal collectors, photovoltaic collectors, and heat storage. Annual behavior of energy loads of the public swimming pool building during a typical meteorological year and the polygeneration system are modeled and simulated using TRNSYS software, whereas techno-economic optimization is performed by GenOpt optimization. The results indicated the optimal configuration of the polygeneration system for the modelled energy demands, as well as the optimal capacity of the polygeneration modules, thus defining the optimal capacity of the polygeneration system for the energy demands of the public swimming pool building.

Key words: *techno-economic optimization, renewable energy sources public swimming pool, polygeneration*

Introduction

Polygeneration can be defined as combined production of two or more energy utilities by using a single integrated process [1, 2]. The high level of integration of a polygeneration system affects the complexity of the system itself, improves overall system efficiency – thermodynamic, environmental, and economic [3]. Polygeneration systems transform available primary energy sources to meet the local final energy demands [4]. Configuration of a polygeneration system should be defined to meet the local energy demands taking advantage of available integrated energy transformation technologies in a best possible way. A polygeneration system may consist of both conventional and renewable energy technologies, and as such may be considered a hybrid energy system. Polygeneration systems may be considered more complex than the conventional systems, with high dependency between locally produced utilities.

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Design and planning of polygeneration systems is a challenging optimization problem, which includes thermodynamic, environmental and economic system efficiency [2]. Optimization of polygeneration systems focuses either on system operation parameters and strategy or on system configuration [1-16]. In this paper, a method for determination of the optimal configuration and capacity of polygeneration system is presented. The method is applied to a model of a public swimming pool building [5], and the optimal configuration and capacity of a polygonation system for this case study is determined.

The public indoor swimming pool building is modeled as a multi zone building using TRNSYS software. The same software is used to simulate behavior of the modelled polygeneration superstructure for meeting energy demands of the indoor swimming pool building during a typical meteorological year [6]. Modelling indoor swimming pool building energy demands is significantly affected by heat and mass transfer from the swimming pool water to the pool hall ambient [5, 7]. The phenomena of water evaporation from the free water surface of an indoor swimming pool is a significant contributor to the total energy balance of the pool building [7-10]. In this paper, the modelling approach of the pool hall presented in [5] is applied for the simulation purposes, but the evaporation coefficient correlation is determined based on measurements on the selected case study building, the public indoors swimming pool of the Sport and Recreation Center (SRC) Dubocica in city of Leskovac, Serbia.

Applicable polygeneration modules, form a system superstructure of the optimization problem [11, 12]. The superstructure formation of the problem of optimization of configuration of polygeneration systems can used with mixed integer linear programming [11, 12], but the results are limited to optimization of system configuration. In this paper, superstructure is integrated for the technically feasible system and subsystem configurations, which relate to technically feasible system and subsystem module combinations. In this paper, in addition to the conventional heating and cooling technologies, and cogeneration technologies, integration of the polygeneration system superstructure included technologies for utilization of RES. The nominal capacity of the polygeneration system superstructure is defined by the sum of the nominal heating, cooling and electricity production capacities of the modules constituting the polygeneration system, limited to the design load capacities. The following GenOpt optimization algorithms were used [13]: generalized pattern search (GPS), Hooke Jeeves (HJ) algorithm , particle swarm optimization (PSO), and hybrid general pattern search with particle swarm optimization (GPS-PSO). The optimization results obtained using these algorithms for the same simulation model and goal function are compared. Based on the number of optimization steps before convergence and results, the most suitable algorithm for optimization of polygeneration systems is proposed.

Methodology

The methodology applied for determining the optimal configuration and capacity of the polygeneration system is illustrated in fig. 1. This approach is applied for the case study of a public indoor swimming pool building, and its energy demands, but can be considered applicable to other polygeneration optimization problems as well. The TRNSYS simulation model coupled to GenOpt optimization was used to pinpoint the optimal configuration and capacity of a polygeneration system for a livestock farm [2]. The applied method, fig. 1, starts with data acquisition about the location, it is energy demands and local resources, identification of locally applicable energy sources in addition to the conventional sources, determination of design loads, integration of the superstructure of the polygeneration system. With

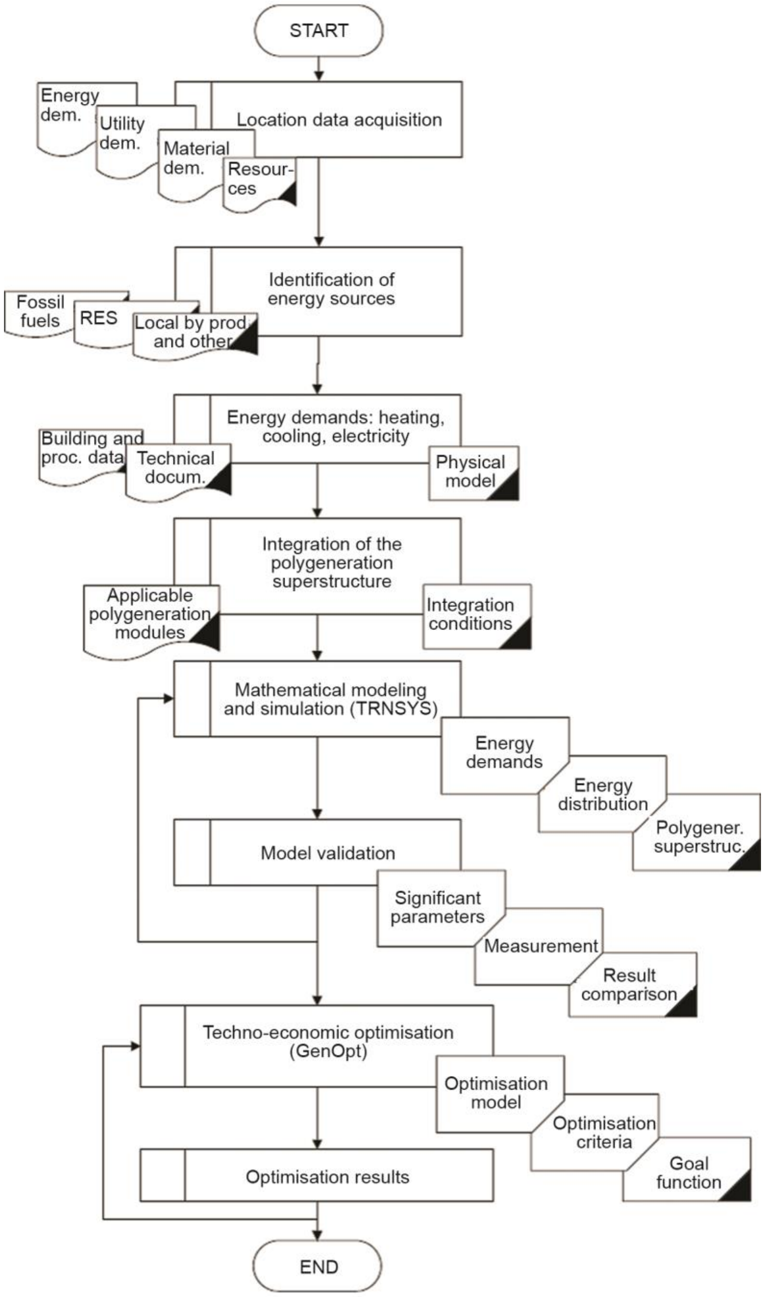


Figure 1. Illustration of the applied method for optimization of polygeneration systems

the defined superstructure consisting of applicable technically feasible polygeneration modules, energy demand, supply and the superstructure of the polygeneration system are modelled and simulated using TRNSYS software. The simulation energy demand and supply model results are compared to the measured data, acquired through measurements on the real object to validate the model. For the validated model, GenOpt optimization is performed, based on the goal function defined according to the economic optimization criteria.

Optimization of the polygeneration system for the energy demands of a public indoor swimming pool building

Techno-economic optimization is performed to determine the configuration and capacity of a polygeneration system for the energy demands of the indoor swimming pool building of the SRC Dubocica in Leskovac. Indoor swimming pool buildings have large energy consumption. The greatest energy consumer is the swimming pool hall where energy is used for maintaining thermal comfort conditions in the hall and pool water [5].

Energy demands of an indoor swimming pool building usually consist of heating demands (space heating, pool water heating, sanitary hot water heating), cooling demands (space cooling), and electricity demands (water treatment, heating, cooling, and other equipment). Energy demands are usually met using conventional systems, such as hot water boilers and vapor compressor chillers, while electricity is supplied from the grid. Application of solar thermal collectors for heating swimming pool water, is well documented in [5, 13-16]. Analysis of application of heat pumps for indoor swimming pools is also showed good effect in terms of energy efficiency [17, 18]. It is assumed that ground source heat pump can be applied to meet the swimming pool buildings heating and cooling loads. Configuration of the polygeneration system superstructure is defined by the modules applicable at the case study location: an internal combustion engine cogeneration module (CHP), a vapor compression chiller (VCC), and adsorption chiller (ADS), a ground source heat pump (HP), flat plate solar thermal collectors (STC), photovoltaic (PV) collectors hot water storage (HWST) and cold water storage (CWST). The design loads for heating and cooling defining the domain of the optimization problem are determined at 3500 kW and 2000 kW. The building is connected to the electricity supply grid, and can export the complete locally produced electricity with respect to the national legislative [20, 21], without the limitation of locally installed electricity production power or local demands. Based on the building layout and it's surroundings, total available area for solar collector installations is limited to 3000 m^2. The model assumes conventional technologiesutilization, hot water boiler (B), VCC, and electric sanitary hot water heaters (AUX) for meeting peak loads, if necessary.

The analyzed optimization problem requires prediction of annual behavior of feasible configurations of the polygeneration system coupled to the energy supply and load model. For this purpose, software tools can be successfully applied [4, 18, 19, 22-28], which enable comparison of annual behavior and effects.

For economic analysis, typically involving estimation of annuity costs of considered systems, software for annual quasi-static simulations during a typical meteorological can be successfully applied, where the analyzed period is divided into *n* simulation timesteps. Hence, decisions about polygeneration system integration, configuration and capacity, apart from technical feasibility conditions, are made based on economic and financial parameters, which form the goal function. Economic parameters, used for such decision making are typically annuity operating costs of the system [29-33], annuity capital investment costs, fuel costs, operation and maintenance costs, [34-36], life cycle costs [37], net present value [33, 38] or levelized product costs [39].

Integration of the superstructure of the polygeneration system

Based on the defined resources the superstructure of the polygeneration system is created to define feasible interactions between system modules. The superstructure consists polygeneration modules which may become part of the optimal configuration, where in technically feasible module interactions are accounted for.

The superstructure integration of a polygeneration module k in the applied optimization model is defined by the numeric value (0 or 1) of the configuration factor, $K_{c,k}$, a function of the resource coefficient, K_k, and consumption coefficients $K_{k,e}$, $K_{k,h}$, $K_{k,c}$.

$$K_{c,k} = K_k K_{k,e} K_{k,h} K_{k,c} \tag{1}$$

The resource coefficient, K_k, is determined following:

For modules k, $k \in [B, CHP]$, representing hot water boilers (B) and cogeneration modules (CHP), which burn fuel at a rate $\dot{m}_g$, higher than the minimum required fuel consumption of the module $\dot{m}_{a\min}$:

$$K_k = \begin{cases} 0 & \text{for} \quad \dot{m}_g < \dot{m}_{g\,\min} \\ 1 & \text{for} \quad \dot{m}_g \geq \dot{m}_{g\,\min} \end{cases} \tag{2}$$

For modules k, $k \in [HP, ADSC, ABSC]$, representing heat pumps (HP), adsorption chillers (ADS), absorption chillers (ABS) which transform heat of a source fluid-flow $\dot{m}_k$, with a source temperature, T:

$$K_k = \begin{cases} 1 & \text{for} \quad \dot{m}_k \geq \dot{m}_{k\,\min}; \quad T_{\min} \leq T \\ 0 & \text{for} \quad \dot{m}_k < \dot{m}_{k\,\min}; \quad T_{\min} > T \end{cases} \tag{3}$$

For solar collector modules k, $k \in [STC, PV]$, representing solar thermal collectors (STC) and photovoltaics (PV), which transform solar energy and require a surface area exposed to solar radiation, A_s, higher than a single collector area $A_{\min}$:

$$K_k = \begin{cases} 1 & \text{for} \quad A_\mathrm{s} \geq A_{\min} \\ 0 & \text{for} \quad A_\mathrm{s} < A_{\min} \end{cases} \tag{4}$$

The resource coefficient is determined by values of local resources determined by data acquisition, but also by resources which may be products of operation of other polygeneration modules.

The electricity consumption factor for modules k, $k \in [CHP, PV]$, representing cogeneration modules (CHP) and photovoltaics (PV) which may produce electricity, is determined based on the local electrical load $P_{pr,e}$, which may also include grid transfer loads.

$$K_{k,e} = \begin{cases} 1 & \text{for} \quad P_{pr,e} > 0 \\ 0 & \text{for} \quad P_{pr,e} = 0 \end{cases} \tag{5}$$

The heat load coefficient of a module k, $k \in [B, CHP, STC, HP]$, representing hot water boilers (B), cogeneration modules (CHP), solar thermal collectors (STC), heat pumps (HP), is determined based on the existance of a heating load $P_{pr,h}$, and the maximum expected heat sink temperature, $T_{pr,h}$:

$$K_{k,h} = \begin{cases} 1 & \text{for} \quad P_{pr,h} > 0; \quad T_{k,pr} > T_{pr,h} \\ 0 & \text{for} \quad P_{pr,h} = 0 \\ 0 & \text{for} \quad T_{k,pr} \leq T_{pr} \end{cases} \tag{6}$$

The cooling load coefficient of a module k, $k \in$ [*ABS, ADS, VCC, HP*], representing absorption chillers (ABS), adsorption chillers (ADS), vapor compression chillers (VCC) and heat pumps (HP) is determined based on the existence of a cooling load $P_{pr,c}$, and the minimum expected heat sink temperature, $T_{pr,c}$:

$$K_{k,c} = \begin{cases} 1 & \text{for} \quad P_{pr,c} > 0 \quad T_{k,pr} < T_{pr,c} \\ 0 & \text{for} \quad P_{pr,c} = 0 \\ 0 & \text{for} \quad T_{k,pr} \le T_{pr,c} \end{cases} \tag{7}$$

Mass-flow rates and temperatures of fuels and operating fluids used to determine integration factors based on eqs. (2)-(7), are determined based on nominal values of equipment manufacturers, and acquired location data.

Mathematical modeling and simulation of the energy loads of the indoor swimming pool building

The modelling approach for indoor swimming pools presented in [5] is applied to model the indoor swimming pool building analyzed in the paper. The pool water temperature change is calculated [5]:

$$\rho_{\mathrm{w}} c_{p\mathrm{w}} V_{\mathrm{p}} \frac{\mathrm{d}T}{\mathrm{d}\tau} = \dot{Q}_{\mathrm{aux}} - (\dot{Q}_{\mathrm{fw}} + Q_{\mathrm{evap}} + Q_{\mathrm{conv}} + Q_{\mathrm{rad}}) =$$
$$= \dot{Q}_{\mathrm{aux}} - \dot{Q}_{\mathrm{fw}} - A_{\mathrm{p}} \left[\dot{E}r + \alpha(T_{\mathrm{w}} - T_{\mathrm{air}}) + \varepsilon\sigma(T_{\mathrm{w}}^4 - T_{\mathrm{wall}}^4) \right] \tag{8}$$

where evaporation heat losses, Q_{evap}, are a function of mass-flow rate of evaporated water, $\dot{E}$, and the latent heat of evaporation, r, heat transfer by convection from the water surface, Q_{conv}, is a function of the convective heat transfer coefficient, α, temperature of the pool water, T_{w}, and the indoor air temperature in the pool hall, T_{air}, is radiation losses Q_{rad} is the function of the emissivity, ε, [–] the Stefan-Boltzmann constant σ = $5.67 \cdot 10^{-8}$ [W/m^{2}K^4], and temperature of the indoor wall surface, T_{wall}, Q_{fw} is the heat loss caused by supply of fresh water, and Q_{aux} is the heat gain from auxiliary heating equipment. The total water surface of the pool water area, A_{p}, is 1480 m^2.

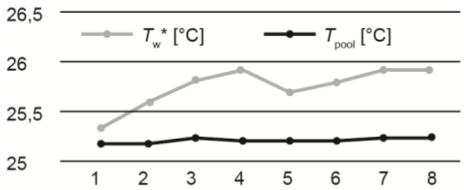
The phenomena of water evaporation from the free water surface of an indoor swimming pool is a significant contributor to the total energy balance of the pool building, but mathematical correlations for determining the evaporated water from the swimming pool surface show significant discrepancy according to [5, 7-10]. In this paper, a correlation was created for determination of rate of water evaporation from the swimming pool surface based on the measurement results in the swimming pool building of SRC Dubocica in city of Leskovac [40]. The mathematical representation of the correlation obtained from the measurement results is:

$$\dot{E} = \frac{(AV_a^N + B)(p_{sw} - \varphi p_{\mathrm{air}})}{r} \tag{9}$$

where A, B, and N are the correlation constants usually acquired through experiment, V_{air} – the velocity of air over the water surface, r – the latent heat of evaporation of water, and φ – the relative humidity of air. The term in the second bracket in eq. (9) represents the vapor pressure difference between the saturated air directly above the pool surface and the pressure of the air in the space higher above the water level (*i. e.* pool hall air). For the best fit with the measured results, the correlation coefficients are determined as: A = 0.019895125, B = 0.089299066, and N = 0.786.

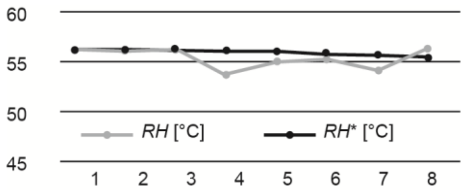
The indoors swimming pool building is modelled as a multizone building in TRNSYS software, with the building envelope properties described in [5], thus determining the annual behavior of heating and cooling loads. Although electric loads can be modelled using the bottom-up approach [28], this was not performed, since complete local electricity production is assumed to be transferred to the grid. In this paper, the building was modelled as multi-zone in TRNSYS software, with typical masonry construction with respect to [5]. Air velocity of 0.08 m/h in the swimming pool hall was assumed constant, determined based on the measured data. The simulation was done with Meteonorm hourly weather data, which included mains water temperature used for fresh water supply.

The simulated results for the same ambient temperatures were compared with the measured results, figs. 2-4. The comparison of the results showed acceptable difference of results. The presented values of the simulated data in figs. 2-4 are rounded to values with two decimal places.



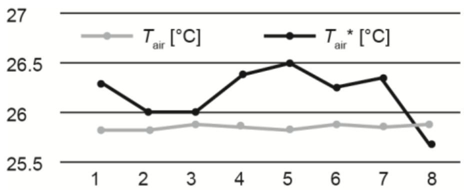
T_w [°C]	T_{pool} [°C]	T_w [°C]	T_{pool} [°C]
25.5	25.38	25.9	25.40
25.8	25.39	26.0	25.40
26.0	25.39	26.1	25.40
26.1	25.39	26.1	25.41

Figure 2. Measured pool water temperature, T_{pool}, and simulated pool water temperature, T_w



*RH** [%]	*RH* [%]	*RH** [%]	*RH* [%]
57.0	56.55	54.4	56.19
56.7	56.70	55.1	55.82
56.7	56.74	52.8	55.57
51.7	56.51	56.8	55.31

Figure 3. Measured relative humidity of the pool hall air, RH*, and the simulated relative humidity of the pool hall air RH



T_{air} [°C]	T_{air}* [°C]	T_{air} [°C]	T_{air}* [°C]
26.14	26.5	26.14	26.7
26.14	26.3	26.15	26.5
26.14	26.3	26.15	26.6
26.14	26.6	26.15	26.0

Figure 4. Simulated air temperature in the pool hall, T_{air}, compared to the measured temperature of pool hall air, T_{air}*

Polygeneration system model

The polygeneration system model includes the models of existing boilers and VCC, which are engaged when other equipment modules are not capable of meeting the given utility loads at a given time step. The highest operation priority is given to the polygeneration modules for utilization of RES (STC, HP) and waste heat (ADS). The model also assumes the possibility of utilization of auxiliary electric heaters for sanitaty hot water (SHW) heating, with the lowest priority. It is assumed that the consumer is connected to the electricity supply grid, and exports the complete locally produced electricity with respect to the national legislative [20, 21]. The operating strategy envisages the following desired heat storage tank temperatures: 7 ºC for the CWST, 50 ºC for the HWST, and 60 ºC for the SHW tank. The system operation strategy assumes indoor temperature monitoring and continuous system operation during a typical meteorological year.

The part load behavior of the polygeneration modules were modelled using equipment normalized performance data found in [2]: for the cogeneration based on internal combustion engines [35, 41-43], for solar sorption integrated systems [44-46], for vapor compression heat pumps [47-49], for PV [50, 51]. The part load performance of the other polygeneration modules are based on the manufacturer performance data: STC [52-55] VCC [58]. Modeling of electricity consumption was limited to the consumption for the purposes of running the modelled heating and ventilation system in addition to the polygeneration system, which accounts for most of the building electricity consumption, due to difficulties of prediction of electricity consumption during a typical year [57]. The simulation time step of 5 minute was adopted as recommended for better accuracy [5].

Total nominal power for heating, $P_{\mathrm{heat.POLY}}$, cooling, $P_{\mathrm{cool.POLY}}$, and production of electricity, $P_{\mathrm{e.POLY}}$, of the polygeneration system is equal to the sum capacities of polygeneration modules, *k*, active in the analyzed configuration of the polygeneration system over *n* simulation timesteps of the typical meteorological year:

$$P_{\mathrm{h,POLY}} = \sum_{i=1}^{n} \left(\sum_{K} q_{hK,i} \right) \tag{10}$$

$$P_{\mathrm{c,POLY}} = \sum_{i=1}^{n} \left(\sum_{K} q_{cK,i} \right) \tag{11}$$

$$P_{\mathrm{e,POLY}} = \sum_{i=1}^{n} \left(\sum_{K} w_{eK,i} \right) \tag{12}$$

Annual production of electricity, $W_{\mathrm{net.POLY}}$, by the analyzed configuration of the polygeneration system can be determined as the difference between total simulated local electricity production, w_{eK}, of the active polygeneration modules, *eK*, and simulated consumption of electricity, W_{uK}, of the active polygeneration modules, *uK*, which require electricity for their operation:

$$W_{\mathrm{net,POLY}} = \sum_{i=1}^{n} \left[\sum_{(eK)} w_{eK,i} \right] - \sum_{i=1}^{n} \left[\sum_{(uK)} w_{uK,i} \right] \tag{13}$$

Heat load of the conventional heating system for the analyzed building model during a typical meteorological year, $Q_{h.a}$, are used to determine boiler fuel consumption, q_{hBa}, and energy consumption of auxilliary heaters, $q_{h\text{AUX}a}$:

$$Q_{h,a} = \sum_{i=1}^{n} (q_{hBa,i} + q_{hAUXa,i}) \tag{14}$$

Cooling load of the conventional cooling system during a typical meteorological year, $Q_{c,a}$, is used to determine the VCC annual cooling energy production, $q_{c\text{VCC}a}$:

$$Q_{c,a} = \sum_{i=1}^{n} (q_{c\text{VCC}a,i}) \tag{15}$$

Energy savings achieved by application of the polygeneration system for heating, $Q_{h,r}$, and cooling, $Q_{c,r}$, compared to the conventional system:

$$Q_{h,r} = Q_{c,\text{POLY}} - Q_{h,a} \tag{16}$$

$$Q_{c,r} = Q_{c,\text{POLY}} - Q_{c,a} \tag{17}$$

Conventional modules, *i. e.* boilers and chillers, also take part in the optimization superstructure, but with the attributed lower rank of operation start compared to the other modules, they are primarily considered for peak loads. Values of the energy streams of each variable in the eqs. (10)-(17) are determined based on the TRNSYS simulation model for each polygeneration superstructure defined by the optimization model.

Techno-economic optimization criteria

Application of a highly integrated polygeneration systems analyzed in this paper can lead to significantly high initial capital investments. Economic performance model of analyzed configuration of such systems is important for providing information for decision making. Based on the literature, the net present value (NPV) of an investment project can be considered the most reliable parameter for assessment of the efficiency of the investment project [58]. The NPV of a polygeneration investment project is used as the goal function for optimization. The economic life of the project of 12 years is assumed, which is the period which corresponds to the contract period for subsidies for export of electricity in Serbia [20, 21]. The goal function is the maximum value of the *NPV*, a function of initial capital investment, I_o, and the discounted value of annuity cash flow during the economic life of the project, B_t, for the year t = (1, 2, 3 … 12), and the discount rate d:

$$NPV = -\sum I_k + \frac{\sum_{0}^{12} B_t}{1 + d^t} \tag{18}$$

The discount rate is a function of change of prices, inflation rate and cost of capital [59]. Cost of capital can also account for opportunity costs. Total annual costs are a sum of heating costs, $B_{h.r}$, cooling costs, $B_{c.r}$, and net electricity cost or electricity profit from subsidies, B_e:

$$B_t = B_{h,r} + B_{c,r} + B_e \tag{19}$$

Annual energy savings is a function of energy or fuel consumption, Q_{fK}, of the active polygeneration modules, k, specific operation cost of the module, C_{fK}, and annual operation and maintanance cost, $B_{ko\&m}$. The annual energy saving achieved by the polygeneration system, Q_{fK}, is determined based on the simulated performance, $q_{fK,i}$, of an active polygeneration module, k, during a simulation timestep, i, with polygeneration modules k, $k \in$[B, CHP, GSHP, STC, VCC, ADSC, PV].

$$Q_{fK} = \sum_{i=1}^{n}(q_{fK,i}) \tag{20}$$

$$B_{h,r} = Q_{fB}C_{fb} + Q_{f\text{AUX}}C_{f\text{AUX}} + B_{Bo\&m} - \sum_{K}(Q_{hfK}C_{fK} + B_{Ko\&m}) \tag{21}$$

$$B_{c,r} = Q_{f\text{VCC}}C_{fb} + B_{Bo\&m} - \sum_{K}(Q_{cfK}C_{fK} + B_{Ko\&m}) \tag{22}$$

Cost of operation and maintenance can be determined as a percentage of equipment purchase cost. Operation costs of polygeneration modules are determined based on fuel or electricity costs, whichever applicable. Profit achieved from electricity export subsidies is determined according to official tariffs [20, 21], and can be calculated as a sum of electricity export from the PV system and cogeneration system:

$$B_e = B_{e\text{CHP}} + B_{e\text{PV}} = \sum_{i=1}^{n}(W_{e\text{CHP},i}C_{e\text{CHP}} + W_{e\text{PV},i}C_{e\text{PV}}) \tag{23}$$

Initial capital investment of a polygeneraton module, k, is a function of it's power, capacity, surface area for solar collectors or storage volume for storage tanks [2]. Total initial capital investment of a module, k, of the superstructure is:

$$I_K = \begin{cases} C_{pK}P_K(1+C_{sc}), & \text{for} \quad K \in (CHP, VCC, GSHP, ADSC, HWST, CWST, PV) \\ C_{pK}A_K(1+C_{sc}), & \text{for} \quad K \in (STC) \end{cases} \tag{24}$$

where C_{pK} [€/kW] is a factor of the purchase cost of a module, C_{SC} (C_{SC} < 1) is the cost of integration of a module in the polygeneration system given as a share of the purchase cost. The values of factors C_{pK} and C_{SC} can be found in [60-62]. Specific equipment purchase costs are determined based on literature, and can be deterdmined according to tab. 1, [2]. Equipment purchase costs provided in available literature are corrected to the present value by application of purchase costs index for the given type of equipment [63-69].

Table 1. Purchase cost factor

Polygeneration module	Unit	Purchase cost, C_{pK}	Reference
CHP	P [€kW^{-1}e^{-1}]	700 $P_{\text{CHP}e}$	[63]
ADS	[€kW^{-1}c^{-1}]	1050 $P_{\text{ADS}c}$	[64]
GSHP	[€kW^{-1}h^{-1}]	–0.113 P_{hp} + 638.406	[65]
STC	[€m^{-2}]	265 A_{STC}	[66]
PV	[€m^{-2}]	120 A_{PV}	[67, 68]
HWST, CWST	[€m^{-3}]	1050 V_{HWST}; 1050 V_{CWST}	[69]

Results and discussion

Table 2. Values of the goal function at the optimal point

Optimization algorithm	NPV [€]
GPS	2890479.02
HJ	2890479.19
PSO	2860421.42
GPS-PSO	2990480.23

According to the applied methodology, optimization results are obtained by application of TRNSYS simulations [13], and GenOpt optimization [68]. The following optimization algorithms are tested: (1) GPS, (2) HJ algorithm, (3) PSO, and (4) GPS-PSO. The values of goal function at optimal point are compared in tab. 2. A slight difference in the value of goal function can be noted, where the PSO, algorithm pinpointed the lowest function value. Optimization results defining configuration, power and capacity of the optimal polygeneration system determined by the power and capacity of it's constituting polygeneration modules is presented in tab. 3. Considered polygeneration modules, which are not part of the optimal solution are not listed in the table. The results obtained using the four tested algorithms have a strong agreement regarding the configuration of the optimal polygeneration system. The power and capacity of the polygeneration modules constituting the optimal polygeneration system configuration obtained using the tested methods are slightly different, tab. 3. The surface area of the solar thermal collector array is slightly lower than the maximum determined solar collector area reported in [5]. Optimization with the NPV as the goal function favors technologies enabling benefits from electricity export subsidies, since the optimal solution includes both cogeneration and PV modules with values at or near the upper domain boundary.

Table 3. Results of optimization

Optimization algorythm	ADS [kW]	CHP [kW]	CWST [m^3]	STC [m^2]	HWST [m^3]	PV [m^2]
GPS	827.5	2000	32.69	3	165.5	3000
HJ	827.5	2000	126.44	3	165.5	3000
PSO	1475.729	1743.84	84.64	262.9	209.7	2678.5
GPS-PSO	1200	2000	125	250	225	3000

The optimal configuration of a polygeneration system, based on the highest NPV value of the project, consist of a CHP, ADS, STC, and PV. With the highest extreme value of the NPV function obtained using the hybrid GPS-PSO method, this result is considered as the optimal point in the analyzed domain. Hence, other tested methods, although indicating the same configuration, indicate a local extreme point of the goal function. However, as comparison of convergence speed of GenOpt optimization algorithms has shown, GPS-PSO algorithm needs the most optimization simulation steps before convergence [2].

Conclusions

In this paper, techno-economic optimization is performed to determine the configuration and capacity of a polygeneration system for the energy demands of the indoor swimming pool building of the SRC *Dubočica* in Leskovac. A methodology for optimization of polygeneration systems is explained. The methodology is based on performance simulation of the building model, coupled to the polygeneration system model. Modeling and simulation is done using TRNSYS software, while optimization is performed using GenOpt optimization. The presented methodology can be adopted to other polygeneration optimization problems as well.

In order to determine the heating and cooling loads of the indoor swimming pool building, modeling of the swimming pool, its interaction with the pool hall and effects on heating and cooling loads was necessary. For this purpose, measurement results performed in the swimming pool hall of the SRC Dubocica in city of Leskovac were used to determine the evaporation coefficient. In this paper, a correlation for calculating the evaporation rate from the indoor swimming pool was presented. This correlation was used in the simulation model. Validation of the simulation results was done by comparing simulated and measured values of water temperature, air temperature and relative humidity in the pool hall, with a good agreement of the results.

Based on the presented simulation model, the optimization model was formed. A superstructure of the polygeneration system was integrated, consisting of chosen polygeneration modules. The mathematical representation of the criteria for integration of polygeneration system superstructure is presented in the paper. The integration process accounts for resource availability, terms of interaction between polygeneration modules, and demand side conditions.

The goal function of *NPV* of the polygeneration system project was used for GenOpt optimization. The economic model for analysis of polygeneration systems used for the optimization is presented in the paper, with a model for determination of initial capital investment cost based on the power and capacity of polygeneration modules which constitute the analyzed polygeneration system.

Finally, techno-economic optimization of the polygeneration system for the energy demands of the indoor swimming pool was performed. The configuration of the optimal system consists of a CNP, ADS, STC, and PV. The optmisation method results included significant production capacity using both PV and CNP, which indicates high impact of electricity export subsidies on the value of the goal function, resulting in configurations favoring polygeneration configurations with high electricity export potential.

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