OPTIMIZATION OF A POLYGENERATION SYSTEM FOR ENERGY DEMANDS OF A LIVESTOCK FARM

by

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A polygeneration system is an energy system capable of providing multiple utility outputs to meet local demands by application of process integration. This paper addresses the problem of pinpointing the optimal polygeneration energy supply system for the local energy demands of a livestock farm in terms of optimal system configuration and optimal system capacity. The optimization problem is presented and solved for a case study of a pig farm in the paper. Energy demands of the farm, as well as the super-structure of the polygeneration system were modelled using TRNSYS software. Based on the locally available resources, the following polygeneration modules were chosen for the case study analysis: a biogas fired internal combustion engine co-generation module, a gas boiler, a chiller, a ground water source heat pump, solar thermal collectors, photovoltaic collectors, and heat and cold storage. Capacities of the polygeneration modules were used as optimization variables for the TRNSYS-GenOpt optimization, whereas net present value, system primary energy consumption, and CO_2 emissions were used as goal functions for optimization. A hybrid system composed of biogas fired internal combustion engine based co-generation system, adsorption chiller solar thermal and photovoltaic collectors, and heat storage is found to be the best option. Optimal heating capacity of the biogas co-generation and adsorption units was found equal to the design loads, whereas the optimal surface of the solar thermal array is equal to the south office roof area, and the optimal surface of the PV array corresponds to the south facing animal housing building rooftop area.

Key words: *polygeneration, techno-economic optimization, biogas, solar energy, absorption, photovoltaic, heat pump, livestock farm*

Introduction

Polygeneration can be defined as combined production of two or more energy utilities by using a single integrated process [1]. The utility outputs of the polygeneration system are typically energy outputs such as heating, cooling, and electricity (*i. e.* trigeneration), but also material products such as biofuels, water, methanol or other compounds. The high level of integration of a polygeneration system affects the complexity of the system itself, but improves overall system efficiency – thermodynamic, environmental, and economic [2]. In order to meet the local final energy demands, polygeneration systems can transform available energy of one or more primary energy sources [3]. The term *polygeneration* in the context of a

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system for providing multiple utilities, developed over time from the adopted term *co-generation* (combined heat and power), and tri-generation (combined heating, power, and cooling) proposed initially by the General Electric company [4]. With further process integration additional utility demands could be met by a single integrated polygeneration system.

This paper addresses technical and economic feasibility of application of renewable energy based hybrid polygeneraton for the utility demands of livestock farms. TRNSYS software was used for modelling of annual energy demands of the farm, as well as modelling of the polygeneration system. The polygeneration system was modelled so that the configuration and production capacity of the system are a functions of optimization variables. Although energy demands of the farm case study are represented predominantly by heating and electricity, the applied optimisation methodology could be used for design and planning of polygeneration systems for other consumers. The aim of this paper is to pinpoint the optimal polygeneraton system configuration and optimal capacity of the hybrid polygeneration system. The applied method includes GenOpt optimization coupled to TRNSYS dynamic simulation polygeneration system model and energy demand model, with adopted temporal precision [5]. In addition, an effort has been made to determine the most efficient GenOpt optimisation method for such optimisation problems.

Optimization of polygeneration systems

As a consequence of high level of integration, polygeneration systems may be considered more complex than conventional systems, with high dependency between locally produced utilities. A polygeneration system consists of two or more polygeneration modules: (1) a cogeneration module (typically a gas turbine or an internal combustion generator set), applied to meet heating and electricity demands (2) sorption cooling modules (adsorption or absorption) applied to utilize heat to meet the cooling demands, (3) production of biofuels or waste to energy technologies, applied for biomass or waste conversion to fuels, electricity and/or other chemical compounds, (4) vapour compression chillers applied to meet the cooling demands, (5) technologies for utilization of renewable energy sources (RES) which can be integrated with the rest of the system, and (6) heat storages.

Hence, design and planning of a polygeneration system is a challenging optimization problem, which involves consideration of thermodynamic, environmental, and economic system efficiency. Optimisation of polygeneration systems focuses either on system operation parameters and strategy or on system configuration [1-16]. Various approaches for optimization of integrated energy systems can be found in literature. The simplest optimization methods are based on comparison of system behaviour in different scenarios [17], or graph methods [11]. Linear programming can be used for optimization when mathematical model of the system is linear or transformed to a linear model [18, 19]. Mixed integer linear programming (MILP) methods are mostly used for configuration optimization problems [11, 13-15, 20-29]. Recent papers on optimization of polygeneration systems show advantages of application of genetic algorithms and evolution algorithms, as described by Ghaeby [30]. Optimization based on genetic algorithms were successfully used for optimization of integrated energy systems [28, 31-34]. The problem of resource availability is also significant for hybrid polygeneration energy systems with a high ratio of RES utilization technologies, such as solar thermal [35, 36], photovoltaics (PV) [32], and systems with thermal storage [37].

For the prediction of system performance software modelling tools are frequently applied in polygeneration analysis [3, 6, 8, 9, 17, 38, 39, 40] where system performance simulation is used to test effects of possible scenarios or for parametric analysis. A review of software for simulation of energy system performance [41] presents possibilities of energy system performance modelling and simulation using recent software tools.

Due to complexity of hybrid polygeneration systems (*i. e.* highly integrated systems), compared to conventional energy systems (*i. e.* independent units for individual production of each of the utilities), an accurate techno-economic analysis of polygeneration systems is important [18]. Economic or financial parameters are usually used as decision variables for assessment of integrated energy systems. The economic decision parameters range from annual operation costs [18, 23, 27, 38, 42, 43], annuity capital cost sometimes combined with fuels costs and operation and maintenance (O&M) costs [35, 44, 45], life cycle costs (LCC) [25, 32], net present value (NPV) [27, 33], and cost rate of product (CRP) [30]. Apart from economic optimization criteria, environmental and/or energetic criteria are also used for optimization of integrated energy systems. Reduction of greenhouse gas emissions is usually accounted as CO_2 emission reduction and used as an optimization variable [23, 24, 32, 43]. Many authors evaluate performance of a polygeneration system based on achieved primary energy saving (PES) obtained compared to the performance of conventional systems designed to meet the same energy loads [15, 18, 33, 38, 46].

Energy efficiency of livestock farms

Livestock farming is a significant part of the agriculture market in Serbia, with high potential for meat export [47] and significant production potentials [48]. Energetic and environmental performance of livestock farms in literature shows significance of this sector, favouring biogas co-generation (CHP) as an energy option, but neglecting penetration of RES and application of polygeneration. The most energy efficient pig and dairy farms are intensive farms, where high production is combined with low energy consumption [49]. One fifth of the world's pork production takes place in the EU, hence, an important socio-economic factor [50]. Research of energy consumption of Danish livestock farming indicated energy use of 20 MJ per kg of live weight pig produced [51]. Analysis of the estimated potential for energy savings in EU farms showed potential for saving of up to 47% by using manure for energy production [50], but utilization of other energy technologies was omitted from the study. Organic farming can also reduce fossil fuel use, but it decreases the production rate [52]. Biogas production on livestock farms improves both waste management and energy supply with best economic feasibility [53-60]. Application of biogas as renewable energy enables recycling of the organic waste, reduces the use of fertilizer, and contributes to the reduction of the greenhouse gas methane [39], but the composition of input substrate affects biogas yield [54]. An economic analysis indicated favourable biogas CHP economic feasibility [55], but this as well as other RES applications can be effected by non-technical barriers [57, 58]. Comparison of eight waste to energy technologies indicated that biogas production provides cheaper CO_2 reduction than incineration, and the lowest CO_2 reduction cost [59]. A study of economic feasibility of electricity generation from biogas in small pig farms showed that the payback period of the biogas production is significantly influenced by the equipment for H_2S removal, but the study assumed a 45% subsidy [18]. The annual performance data gathered through an energy audit and the results of a steady-state energy balance of the farm and its major energy processes used to generate most profitable energy supply technologies [61, 62] pinpointed biogas CHP as the most profitable option. Hence, biogas applications including biogas co-generation and electricity production, which lead to positive economic an environmental effects [63-68], are an inevitable part of a livestock farm energy system case study, whereas application of other polygeneration technologies on livestock farms are not as present in the literature.

Methodology

The methodological approach performed in this paper was aimed to pinpointing the optimal polygeneration system configuration and the optimal capacity as a retrofit option of an existing facility, however, it is also applicable for planning new facilities.

The methodology envisages the following: (1) data acquisition about the location, main energy and material streams and main utility consumers, (2) identification of the applicable locally available renewable energy sources, (3) identification of the applicable conventional energy sources, (4) acquisition and/or computation of the heating and cooling design load data, (5) generation of the applicable polygeneration technologies, (6) modelling of the dynamic annual utility demand performance, (7) modelling of the polygeneration superstructure model based on the chosen polygeneration constituent modules, and (8) optimization of the configuration capacity of the polygeneration system based on economic, energetic and environmental criteria.

It is assumed that the modelled polygeneration system has heating and cooling capacities lower than or equal to the design load, whereas the peak loads or loads occurring in the periods with insufficient availability of renewable energy sources are met using conventional technologies and/or grid electricity. Configuration of the optimal polygeneration configuration and capacity is pinpointed for each of the three optimisation criteria.

The case study of a pig farm

In this paper, a case study of an integrated pig farm with the annual production capacity of 32,000 fatlings with 1,350 sows is chosen for optimization. Animals are housed in sections according to the stage of breeding process they are in, which also determines heat demands of these buildings [68]. Temperature in the buildings for animal housing is maintained throughout the rearing process according to the breeding stage. There are six animal housing buildings at the farm, three of which are heated to an indoor temperature necessary for ensuring animal health. In addition, an office building is heated and cooled, and a 30001 sanitary hot water (SHW) tank is heated to 60 ºC. The design heating load of the farm of 1500 kW is met by two identical boilers. The main utility demands are space heating, sanitary hot water heating, and electricity demands. Apart from these, agricultural production on 390 ha has a demand for significant quantities of fertilizer, estimated to 120-180 kg/ha, locally produced manure is used as fertilizer. The farm has a position open to solar radiation, underground water wells and organic waste which could be used as local resources.

Mathematical modelling and numerical simulation of the farm polygeneration system

The farm was modelled as a multi-zone building using TRNSYS software, which included the animal housing buildings and the office building. The simulated annual heating demands for a typical meteorological year [69] was found 6.34% higher than the actual heat consumption determined by annual farm fuel consumption for the year of the data collection [61]. Demands of the SHW system were modelled using the bottom-up approach, based on a typical daily use scenario. Acquired annual electricity consumption data [61] account for electricity consumption of the equipment and appliances at the farm, which is not modelled within the scope of this paper. Meteonorm hourly weather data [69] are used to account for the annual change of the ambient temperature and humidity, as well as the mains water temperature for the fresh water supply of the SHW heating system.

Monthly values of the simulated heating, cooling and sanitary hot water heating demands are presented in fig. 1. With the cooling demand of the office building significantly lower than the heating demands and SHW heating demands, animal housing building heating can be considered the greatest energy consumer at the farm. The control strategy for the animal housing buildings is based on the desired indoor temperature, defined based on recommended values for pig farms [68]. A fan coil system is modelled for heating purposes, with up to 30% of fresh air supply in the heating regime. It is assumed that the animal housing buildings are ventilated using fresh air during summer, whereas the office building is cooled using a typical vapour compression chiller.

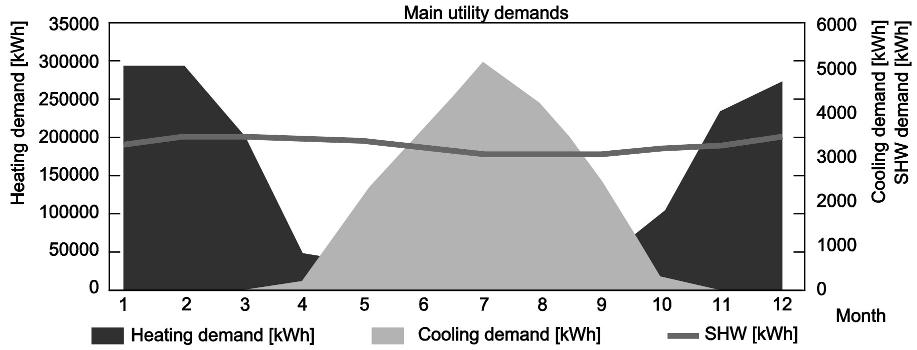

Figure 1. Simulated annual demands: heating, cooling and sanitary hot water

The polygeneration system super-structure, fig. 2, is coupled to the utility demand model, fig. 3, with focus on heating, cooling, and SWH heating demands. With respect to the on-site solar energy potential, ground water and biogas production from local organic waste, the polygeneration system super-structure was modelled consisting of: (1) a PV array, (2) a ground source heat pump (GSHP), (3) a olar thermal collector array (STC), (4) a hot water fired adsorption chiller (ADSC), (5) a gas fired cogeneration based on an internal combustion engine generator set (CHP), (6) a gas fired boiler (B), (7) vapour compression chiller (VCC), (8), a hot water storage tank (HWST), and (9) a cold water storage tank (CWST). Total heating and cooling capacity of the polygeneration system without the STC was limited to the heating design load of the buildings.

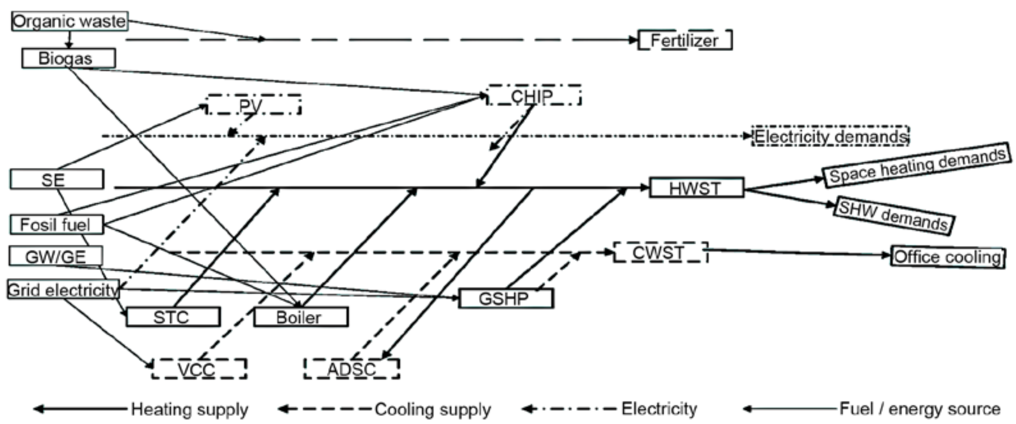

Figure 2. Scheme of the super-structure of the farm polygeneration system

The polygeneration system model includes the models of existing boilers (B) and chiller (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, GSHP) and waste heat (ADSC). The model also assumes the possibility of utilization of auxiliary electric heaters for SHW heating, which are currently used at the farm, with the lowest priority. It is assumed that the farm is connected to the electricity supply grid, and exports the complete locally produced electricity with respect to the national legislative [70, 71]. Scheme of the simplified heating and cooling TRNSYS utility supply model is presented in fig. 3. 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.

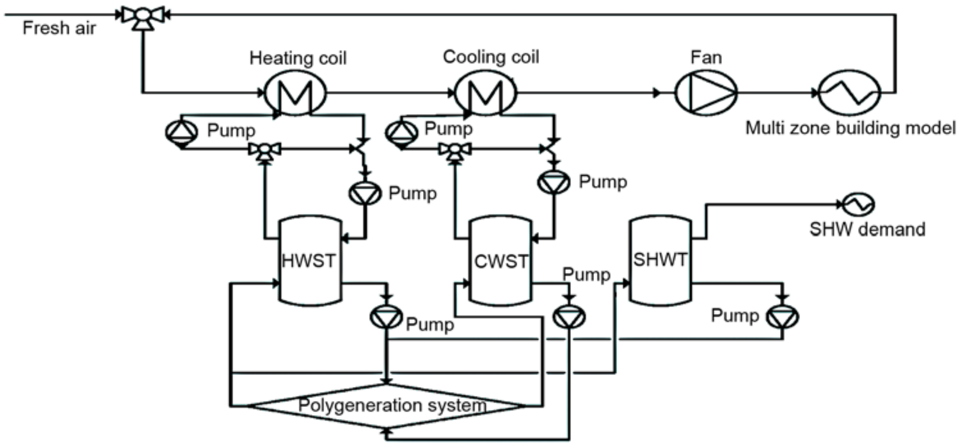

Figure 3. Scheme of the heating and cooling supply model

The part load behaviour of the polygeneration modules were modelled using equipment normalized performance data found in literature: for the co-generation based on internal combustion engines [35, 72, 73], for solar sorption integrated systems [74-76], for vapour compression heat pumps [77-80], for PV [80, 81]. The part load performance of the other polygeneration modules are based on the manufacturer performance data: solar thermal collectors [82], vapour compression chillers [83]. The simulation time step of 5min was adopted as recommended for better accuracy [5].

The total annual heating $Q_{\mathrm{h,POLY}}$, cooling $Q_{\mathrm{c,POLY}}$, and electricity production $W_{\mathrm{e,POLY}}$ can be calculated as sum of production rates for all of the constituting components for the n time steps corresponding to one year (eqs. 1, 2, and 3), based on component model K production heating cooling and electricity production rates during each of the simulation time steps i:

$$Q_{\mathrm{h,POLY}} = \sum_{i=1}^{n} q_{\mathrm{h}K,i} = \sum_{i=1}^{n} (q_{\mathrm{hCHP},i} + q_{\mathrm{hB},i} + q_{\mathrm{hSTC},i} + q_{\mathrm{hGSHP},i} + q_{\mathrm{hAUX},i}) \tag{1}$$

$$Q_{\mathrm{c,POLY}} = \sum_{i=1}^{n} q_{\mathrm{c}K,i} = \sum_{i=1}^{n} (q_{\mathrm{cVCC},i} + q_{\mathrm{cGSHP},i} + q_{\mathrm{cADS},i}) \tag{2}$$

$$W_{e,POLY} = \sum_{i=1}^{n}(w_{eK,i}) = \sum_{i=1}^{n}\left(w_{eCHP,i} + w_{ePV,i}\right) \tag{3}$$

The annual net electricity production $W_{\text{net,POLY}}$ of the polygeneration system can be calculated by subtracting simulated electricity consumption of the modules which utilize electricity for their operation $W_{u\text{CHP},i}$ and $W_{\text{ePV},i}$ (eq. 4). Parasitic electricity loads of the modelled fans, pumps and similar equipment is considered negligible.

$$W_{\text{net,POLY}} = W_{\text{e,POLY}} - (W_{u\text{VCC}} + W_{u\text{GSHP}}) = \sum_{i=1}^{n}(w_{\text{eCHP},i} + w_{\text{ePV},i}) - \sum_{i=1}^{n}(w_{u\text{VCC},i} + w_{u\text{GSHP},i}) \tag{4}$$

The performance of the polygeneration system is compared to the performance of the conventional on site system, defined by the simulated boiler and chiller performance, and auxiliary electric SHW heaters:

$$Q_{\text{h,a}} = \sum_{i=1}^{n}(q_{\text{hBa},i} + q_{\text{hAUXa},i}) \tag{5}$$

$$Q_{\text{c,a}} = \sum_{i=1}^{n} q_{\text{cVCCa},i} \tag{6}$$

Reduction of consumed energy for heating $Q_{\text{h,r}}$ and cooling $Q_{\text{c,r}}$ achieved by application of the polygeneration system compared to the conventional system installed on the farm, can be calculated according to:

$$Q_{\text{h,r}} = Q_{\text{c,POLY}} - Q_{\text{h,a}} \tag{7}$$

$$Q_{\text{c,r}} = Q_{\text{c,POLY}} - Q_{\text{c,a}} \tag{8}$$

Available farm slurry for methane production is estimated to 74.6 t per day, with a constant biogas yield of 27.5 m^3 per ton of fresh slurry [68]. For this estimation, a ratio of methane in produced biogas of 60% is assumed, and internal combustion engine is chosen as best cogeneration technology [61, 64]. It is assumed that the polygeneration CHP and B modules consume locally produced biogas, and natural gas when the fuel consumption exceeds the local production rate. Natural gas consumed by the polygeneration module is calculated:

$$Q_{\text{g,POLY}} = \begin{cases} 0, & \text{for} \quad Q_{\text{fCHP}} + Q_{\text{fB}} < Q_{\text{bio}} \\ Q_{\text{fB}} + Q_{\text{fCHP}} - Q_{\text{bio}}, & \text{for} \quad Q_{\text{fCHP}} \geq Q_{\text{bio}} \end{cases} \tag{9}$$

where $Q_{\text{g,POLY}}$ is the annual natural gas consumption of the polygeneration system, Q_{fB} – the annual gas consumption of the boiler, Q_{fCHP} – the gas consumption of the CHP module, and Q_{bio} – the annual biogas production.

Optimization of the case study polygeneration system for the demands of the farm

Optimization of the configuration and nominal capacity of the polygeneration system for the demands of the integrated pig farm is performed based on economic, energetic and environmental criteria. Configuration is defined by the modules constituting the polygeneration system, whereas the nominal capacity is defined by the sum of the nominal heating, cooling and electricity production capacities of the modules constituting the polygeneration system. Capacity for production of fertilizer, a consequence of operation of a configuration of the polygeneration system which includes biogas co-generation [61-67], is given secondary significance with negligible impact on the optimisation criteria, since organic waste available for biogas and fertilizer production is applied on the farms land as organic fertilizer. The optimization variables are selected to define the capacity of the polygeneration system: Power of the CHP module (P_{CHP}), heating capacity of the GSHP (P_{GSHP}), cooling capacity of the adsorption chiller module (P_{ADSC}), surface of the solar thermal collector array (A_{STC}), surface of the PV collector array (A_{PV}), volume of the hot water storage tank (V_{HWST}), and volume of the cold water storage tank (V_{CWST}). The optimisation variables are treated as continuous in the analysed domain. The lower boundary for all of the optimization variables is 0, whereas the upper boundaries are: 1500 kW for the heating modules (CHP and GSHP), 20 kW for the cooling module (ADSC), 150 m^2 for STC array, 9000 m^2 for the PV array, 300 m^3 for the HWST, and 10 m^3 for the CWST. Maximum allowed heating capacity without STC, $P_{\mathrm{h,POLY}}$, and cooling capacity $P_{\mathrm{c,POLY}}$ of the polygeneration system is limited by the design heating and cooling loads (D_{h} and D_{c}), so that $P_{\mathrm{h,POLY}} = P_{\mathrm{h,B}} + P_{\mathrm{h,BCHP}} + P_{\mathrm{h,GSHP}} + P_{\mathrm{h,AUX}} \le D_{\mathrm{h}}$, and $P_{\mathrm{c,POLY}} = P_{\mathrm{c,GSHP}} + P_{\mathrm{c,VCC}} + P_{\mathrm{c,ADS}} \le D_{\mathrm{c}}$.

Economic optimization criteria

Application of a highly integrated polygeneration system can require high initial capital investment. As such, decision makers are likely to be most interested in the economic performance of such investments. Bejan defines the term optimization as modification of the structure (*i. e.* configuration) and/or operation parameters of a system in order to minimize total operational costs of system production under the boundary conditions [84]. Typical parameters for determining profitability of investment projects are payback period (simple and dynamic), net present value, financial rate of return, net present value factor and cost benefit factor [85]. However, the net present value (NPV) parameter can be considered the best indicator of project profitability [86, 87]. Hence it is included in the official procedures for evaluating investment projects [88, 89], which includes energy efficiency and renewable energy projects [85, 90]. The NPV value of the polygeneration system investment project was used as criteria of economic optimization with an economic lifetime of 12 years, corresponding to the duration of the of the contract for subsidy electricity export [70, 71]. The maximum value of NPV is used as the goal function for optimization, calculated as a function of the initial capital investment B_0 in the year of project implementation (*i. e.* year 0), total annual savings B_{t} in the year t = (1, 2, 3,…, 12), and the discount rate d:

$$\mathrm{NPV} = -B_0 + \sum_{1}^{12} \frac{B_{\mathrm{t}}}{1+d^{\mathrm{t}}} \tag{10}$$

The discount rate is a function of the cost rate of the financing source(s) [85] and/or opportunity cost rate(s). Total annual savings are calculated as sum of energy cost saving for heating $B_{\mathrm{h,r}}$, $B_{\mathrm{c,r}}$, and electricity export B_{e}:

$$B_{\mathrm{t}} = B_{\mathrm{h,r}} + B_{\mathrm{c,r}} + B_{\mathrm{e}} \tag{11}$$

Annual energy cost savings are calculated as a function of annual energy consumption of a K polygeneration module, $Q_{\mathrm{f}K}$, the specific energy cost rate of that module, $C_{\mathrm{f}K}$, and annual operation and maintenance cost, $B_{K\mathrm{o\&m}}$. It is assumed that the locally produced fertilizer is spread-out on the farms land, instead of current manure spreading, and as such does not have a significant impact on the project cash flows, although it can be considered to be of a higher quality. Annual energy cost savings $Q_{\mathrm{f}K}$ are obtained as a function of simulated energy consumption $q_{fK,i}$ at a simulation time step i of a polygeneration module K, where [$K \in$ (B, CHP, GSHP, STC, VCC, ADSC, VCC, PV)].

$$Q_{fK} = \sum_{i=1}^{n} q_{fK,i} \tag{12}$$

$$B_{h,r} = Q_{fB}C_{fb} + Q_{fAUX}C_{fAUX} + B_{Bo\&m} - \sum_{K}(Q_{hfK}C_{fK} + B_{Ko\&m}) \tag{13}$$

$$B_{c,r} = Q_{fVCC}C_{fb} + B_{Bo\&m} - \sum_{K}(Q_{cfK}C_{fK} + B_{Ko\&m}) \tag{14}$$

Energy cost rates for the polygeneration modules are based on the average farm electricity cost [€ per kWh] [61] and natural gas cost [€ per kWh], whereas the operation and maintenance cost is calculated as a small ratio (3-5%) of the equipment purchase cost. Profit achieved during a typical meteorological year by electricity export B_e is calculated with respect to the electricity export price, where the electricity export cost rate is a function of the nominal system power [70, 71].

$$B_e = B_{eCHP} + B_{ePV} = \sum_{i=1}^{n}(W_{eCHP,\,i}C_{eBCHP} + W_{ePV,i}C_{ePV}) \tag{15}$$

Initial capital investment of each of the components is set as a function of the nominal power or capacity of the polygeneration module or as a linear function of the surface area covered by the solar system (PV or STC) or the volume of the storage tank [91]. A general representation of the initial capital investment I_K for the polygeneration module K is presented as:

$$I_K = \begin{cases} C_{pK}P_K\left(1+C_{sc}\right), & \text{for} \quad K \in (\text{CHP, VCC, GSHP, ADSC, HWST, CWST, PV}) \\ C_{pK}A_K(1+C_{sc}), & \text{for} \quad K \in (\text{STC}) \end{cases} \tag{16}$$

where C_{pK} [€ per kW] is the specific equipment purchase factor, and C_{sc} (C_{sc} < 1) – the system integration costs given as fraction of the equipment purchase cost. The values of C_{pK} can be found in literature, tab. 1. Literature equipment costs are converted to the present values using the equipment cost index factors [91, 92].

Table 1. Specific equipment purchase costs

Polygeneration module	Unit	Specific equipment purchase cost (C_{pK})	Literature
BCHP	€ per kW$_e$	–1.09 P_{CHPe} + 3602	[79]
ADSC	€ per kW$_c$	1050	[80]
GSHP	€ per kW$_h$	–0.116 P_{hp} + 218.325.	[81]
STC	€ per m	265	[82]
PV	€ per m	120	[83] [84]
HWST, CWST	€ per m	1050	[85]

Energetic optimization criteria

Minimum value of the primary energy consumption (PEC), used as indicator of energetic polygeneration system performance, is used as goal function of the second optimization criteria. PEC related to annual operation of the polygeneration system is calculated as sum of primary energy consumptions of the constituting polygeneration modules K, $[K \in$ (B, CHP, GSHP, STC, VCC, ADSC, VCC, PV)] according to [93]:

$$\mathrm{PEC_{poly}} = \sum_K (\mathrm{PE}_{\mathrm{h}K,\mathrm{PE}} + \mathrm{PE}_{\mathrm{c}K,\mathrm{PE}}) - \sum_K \mathrm{PE}_{wK,\mathrm{PE}} \tag{17}$$

where $\mathrm{PEC_{poly}}$ is the primary energy consumption of the polygeneration system, $\mathrm{PE}_{\mathrm{h}K,\mathrm{PE}}$ and $\mathrm{PE}_{\mathrm{c}K,\mathrm{PE}}$ are the primary energies associated to the polygeneration module K for heating and cooling, respectively, and $\mathrm{PE}_{wK,\mathrm{PE}}$ is the primary energy corresponding to electricity local production of electricity of the polygeneration module K.

Environmental optimization criteria

Minimum value of the CO_2 emission of the polygeneration system is used as the criteria defining the third goal function for optimization. The CO_2 emission of the polygeneration system $C_{\mathrm{CO_2,poly}}$ can be calculated with respect to [93]:

$$C_{\mathrm{CO_2,\,poly}} = \sum_K (C_{K,\mathrm{CO_2}} - w_{K,\mathrm{CO_2}}) \tag{18}$$

where $C_{K\mathrm{CO_2}}$ is the annual CO_2 emission obtained as a consequence of the annual operation of the polygeneration module K, and $w_{K\mathrm{CO_2}}$ – the emission reduction consequence of the local electricity production.

Results

The results presented in this paper are obtained using TRNSYS simulation system performance simulation coupled to Genopt [94] optimization algorithms: (1) generalized pattern search (GPS), (2) Hooke Jeeves algorithm (HJ), (3) particle swarm optimization (PSO), and (4) hybrid general pattern search with particle swarm optimization (GPS-PSO). The optimal solutions obtained based on the NPV value, CO_2 emission and PEC value are compared.

The ranges of results obtained with the applied optimisation algorithms are presented in tab. 1 for the modules constituting the optimal configuration. The optimal solution (tab. 1) pinpoints the biogas CHP combined with STC and PV as the optimal solution obtained for all used goal functions, and disposes of the rest of the polygeneration superstructure constituting modules from the optimal configuration. The results of optimisation based on PEC indicated utilization of a small scale GSHP, reduced size of the HWST by up to 14% and CWST up to 5% compared to the solutions obtained for the other criteria (tab. 2).

The tested optimisation methods showed similar results in terms of computed value of the goal functions (fig 4). PSO algorithm showed 1.7% lower value than the maximum calculated value of NPV obtained using HJ and GPS-PSO algorithms. An equal value of PEC at optimal point obtained with HJ and GPS algorithms was 3.6% higher than the optimal value obtained with PSO, whereas values of reduced CO_2 emission of the optimal solutions obtained with either of the tested algorithms were equal. A significant difference of convergence speeds can be found among the tested optimisation algorithms. GPS may be considered the fastest with convergence reached after 9.7-13.6% of the slowest PSO algorithm. Results

Table 2. Results of optimisation

Goal		P_{CHP} [kW]	P_{GSHP} [kW]	P_{ADSC} [kW]	A_{STC} [m^2]	A_{PV} [m^2]	V_{HWST} [m^3]	V_{CWST} [m^3]
NPV	GPS	1500.00	0.00	20.00	150.00	8910.00	300.00	10.00
	HJ	1500.00	0.00	20.00	150.00	8910.00	300.00	10.00
	PSO	1500.00	0.00	20.00	150.00	8910.00	300.00	10.00
	GPS-PSO	1500.00	0.00	20.00	150.00	8910.00	300.00	10.00
PEC	GPS	1462.50	0.00	20.00	148.13	8910.00	287.50	10.00
	HJ	1462.50	0.00	20.00	145.31	8910.00	257.81	10.00
	PSO	1484.95	15.05	4.95	150.00	8910.00	297.83	9.51
	GPS-PSO	1479.50	12.00	8.00	147.80	8910.00	300.00	10.00
CO_2	GPS	1500.00	0.00	20.00	149.06	8910.00	300.00	10.00
	HJ	1500.00	0.00	20.00	149.06	8910.00	300.00	10.00
	PSO	1500.00	0.00	20.00	148.13	8910.00	300.00	10.00
	GPS-PSO	1500.00	0.00	20.00	150.00	8910.00	300.00	10.00

obtained using HJ algorithm differed less than 3.6% from the best solution, however it reached convergence after 12.9 to 18% of the time of the slowest PSO algorithm. The hybrid GPS-PSO algorithm, showed constantly the best extreme values of the goal function, but its convergence was only 11-14% faster than the slowest PSO.

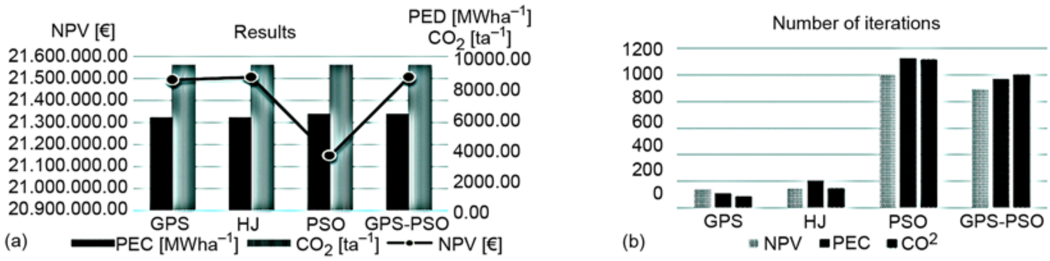

Figure 4. Comparison of results obtained with applied optimisation algorithms: values of goal functions NPV, C_{CO_2}, poly and PEC_{poly} for the optimum solutions (left), and number of iterations before convergence with tested optimisation algorithms (right)

Conclusions

Hybrid polygeneration systems with utilization of renewable energy sources provide economic and environmental benefits, due to the high level of process integration and flexibility of operation. With many available energy sources and technologies with possibility to become part of a polygeneration system configuration, finding the optimal configuration and capacity can be a challenging task in the planning and design phase. A TRNSYS/GenOpt software based approach for optimisation of polygeneration systems with utilization of renewable energy sources was presented in this paper, and applied on a case study of a pig farm. The results indicated that the configuration based on biogas CHP module, ADSC module for cooling, aided by STC can be considered optimal for meeting the heating and cooling loads. A significant PV surface area as part of the optimal solution indicates a high potential for PV penetration in hybrid polygeneration systems. The optimal size of HWST and CWST equal to or close to the maximum boundary values indicate benefits of high capacity heat storages in integration of polygeneration systems. The proposed optimisation method economic criteria pinpoints the optimal configuration and system capacity to maximize the NPV of the system economic lifetime, but neglects the return of investment rate, which is useful for comparing project profitability and specific effectiveness of the initial capital investment.

Optimisation results were obtained using four GenOpt optimisation algorithms, all of which provided similar results. The difference of values of the goal function of the optimal solution of up to 3.6% was found between the tested algorithms. Similar, the tested algorithms indicated similar values of the optimal system configuration and capacities. The greatest disagreement among results was found for the optimisation based on PEC with difference of up to 2.5% of the biogas CHP heating capacity and up to 15% for the HWST. Based on the speed of convergence, and obtained result difference, HJ algorithm can be considered as the fastest, and GPS-PSO as the most accurate in finding the global extreme value point of the goal function for such optimisation problems.

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Nomenclature

A – surface area
B – annual savings, [€]
C – coefficient, [€kW^{-1}h^{-1}], [€kW^{-1}], [€m^{-2}] [ta^{-1}]
D – design load, [kW]
I – initial capital investment, [€]
K – module of the super-structure
NPV – net present value, [€]
PE – component primary energy consumption, [kWh]
PEC – system primary energy consumption, [kWh]
Q – annual heat supply, [kWh]
q – heat rate over a time step, [kJh^{-1}]
W – annual electricity production, [kWh]
w – electricity production over a time step, [kWh]
P – power, nominal power, heating/cooling capacity, [kW]
Q – heating rate, cooling rate, [kWh]
W – electricity production, [Js^{-1}]

Subscripts

a – actual, annual, on-site energy rate
c – cooling, cost
e – electricity
f – fuel, energy input from energy source
g – natural gas, biogas
h – heating
p – purchase
r – reduction, reduced energy rate, reduced cost
u – consumption energy rate
I – simulation time step

Acronyms

ADS – adsorption chillier
AUX – electrical auxiliary heaters
B – boiler
CO_2 – CO_2 emission
CHP – cogeneration, biogas cogeneration
GSHP – ground source heat pump
POLY – polygeneration system
PV – photovoltaic collector array system
STC – solar thermal collector array
VCC – vapour compression chiller

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