Conference Proceedings

EuroSun 2014

Aix-les-Bains (France), 16 – 19 September 2014

Software for the analysis, predesign and performance evaluation of Central Solar Heating Plants with Seasonal Storage

Mateo Guadalfajara, Miguel Ángel Lozano, Luis María Serra and Javier Rodríguez

Aragon Institute of Engineering Research, Dept. of Mechanical Engineering Universidad de Zaragoza, Zaragoza (Spain)

Abstract

The design and calculation of the behavior of Central Solar Heating Plants with Seasonal Storage (CSHPSS) during the year is a complex process requiring detailed climatic and demand data in order to properly design/sizing the plant components to reach the desired solar fraction. The utilization of simple methods for the calculation of these plants allows the sizing of the main components and provides an estimate of the system performance during the year, using easy to find demand and climatic data. In this paper is presented the beta version of a software based on the simple method developed by the authors. The software provides a pre-design of the main components of these systems as well as to establish design criteria of CSHPSS. as well as a preliminary economic and environmental evaluation. The developed software is also very useful to perform economic and environmental analysis to evaluate the CSHPSS systems.

Keywords: software; solar thermal energy; district heating; seasonal storage

1. Introduction

The World energy demand in the residential sector (2035 Mtoe) represents roughly 27% of the final energy consumption (IEA, 2013). The development of solar systems covering part of the residential thermal energy is an economically viable option that reduces the consumption of fossil fuels. Hence, the production of a significant part of this demand with solar energy might solve an important part of the energy problems: shortage, dependency, high prices fluctuation, pollution, climate change, among others (IEA, 2012). The Spanish normative on buildings (CTE, 2006) requires for new buildings, depending on the climatic location, a production with solar energy of 30% to 70% of thermal energy demand of domestic hot water (DHW). Considering also the coverage of other heating demands in buildings as space heating or even cooling with absorption machines, the real potential of the solar thermal energy is very high, almost 75% of the total energy consumed in buildings.

Central solar heating plants with seasonal storage can cover a high solar fraction of the space heating and domestic hot water demands of big communities at an affordable price. These systems already supply heat to big communities through district heating systems in the north and center of Europe. The evaluation of the performance and the design of these centralized solar systems is a complex process, due to their dynamic behavior both during the day and along the year.

The production of the solar collector field depends on the solar radiation and the ambient temperature changing along the day. The behavior and operation temperature of the seasonal storage depends on the demand and solar production distributions along the year. Further, the size of the demand and the location affects to the performance of the system in such way that the design criteria for the north and south of Europe are very different. As a result, the process of pre-design and study in initial stages of the project becomes a real challenge.

Dynamic simulations with TRNSYS (TRNSYS 16, 2004) of CSHPSS provide an evaluation of the performance of its behavior with a high accuracy (Raab et al., 2005; Lundh and Dalenbäck, 2008; Lozano et al., 2010; Guadalfajara et al., 2012; Guadalfajara, 2013) but it requires exhaustive and detailed information

Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.19.12 Available at http://proceedings.ises.org

and a high computational effort. Simple calculation methods requiring less detailed data and a lower computational effort can complement TRNSYS providing a preliminary quick evaluation of the size of the main components of an installation facilitating the design task and providing an estimate of its annual performance (Lunde, 1979; Braun et al., 1981; Guadalfajara, 2013; Guadalfajara et al., 2014a, 2014b).

In this paper is presented a software application for the analysis, pre-design and performance evaluation of CSHPSS using the simple calculation method developed by the authors (Guadalfajara et al., 2014a). The software application is a distributable Engineering Equation Software (EES, 2013) program. It uses public demand and climatic data that can be easily obtained. Data corresponding to several cities from Europe have been initially included in the application (Aberdeen, Amsterdam, Ankara, Athens, Barcelona, Belgrade, Berlin, Bordeaux, Bratislava, Brno, Brussels, Budapest, Cagliari, Chisinau, Copenhagen, Debrecen, Dublin, Firenze, Frankfurt, Grenoble, Goteborg, Hamburg, Helsinki, Innsbruck, Izmir, Kiev, Krakow, Lisbon, London, Lyon, Madrid, Manchester, Marseille, Milano, Minsk, Nantes, Napoli, Odessa, Oslo, Oulu, Palermo, Paris, Porto, Riga, Roma, San Sebastian, Skopje, Sofia, Stockholm, Strasburg, Tallinn, Tirana, Toulouse, Trondheim, Umea, Valencia, Varna, Warszawa, Wien, Zagreb, Zaragoza and Zürich) but more locations can be included by the user. The software calculates the monthly performance of the system, i.e. heat demand, solar production, auxiliary energy required and average storage temperature. The software also calculates the hourly performance of the solar collector field on a typical day each month. It can be used to pre-design the solar field and the volume of the seasonal thermal energy storage of CSHPSS, as well as to perform easily analysis for the evaluation of these systems. The software application evaluates the technical and economic feasibility and the environmental benefits in an early stage of a project, contributing also to establish optimization and design criteria of CSHPSS.

2. Description of the Software

EES is a general equation solver program that can numerically solve thousands of coupled non-linear algebraic and differential equations. EES also contains thermophysical properties of working fluids and common substances used in thermal energy systems. With this software a distributable program has been created for the analysis, pre-design and performance evaluation of CSHPSS systems, based on the calculation methodology proposed by the authors. The program consists of four calculation modules (Guadalfajara et al., 2014a). Module 1 elaborates the climatic and demand data. Module 2 calculates the hourly performance of the solar collector field in a typical day each month. Module 3 calculates the monthly system performance: seasonal storage thermal losses, solar energy produced, auxiliary energy required and seasonal storage temperature. Module 4 calculates the annual results of the system and determines the economic and environmental costs of the thermal energy produced from solar radiation.

Climatic and demand data are used in Module 1 to calculate the system performance in a specific location, selected among those included in the program. The size of the community (number of dwellings) and the design ratios for the area of solar collectors and for the thermal energy storage are user defined parameters. A number of coefficients of performance for the solar collector, the heat exchanger and the seasonal storage can be adjusted. Also economic and environmental parameters can be adapted to specific user defined values. To adjust the design parameters and to analyze the results, six interface windows have been built, starting from general parameters of the system to specific considerations of each component. In these windows the design parameters can be defined and the results are obtained with the help of several graphs and diagrams that support the evaluation of CSHPSS.

In this section is presented the sequential procedure of the software to calculate and pre-design a CSHPSS installation. There are six subsections, corresponding each to a different window available in the developed software: main window, solar collector field, seasonal storage, heating demand, economic evaluation and environmental assessment (Life Cycle Assessment). Each window contains its specific design parameters that can be adjusted by the user, a heading with the name of the window/section as well as explaining information including design parameters values suggested by the authors.

2.1. Main window

The main window of the software is shown in Fig. 1, in which global design variables of a CSHPSS system can be defined and the main results of the system are presented. The window is divided in 6 blocks.

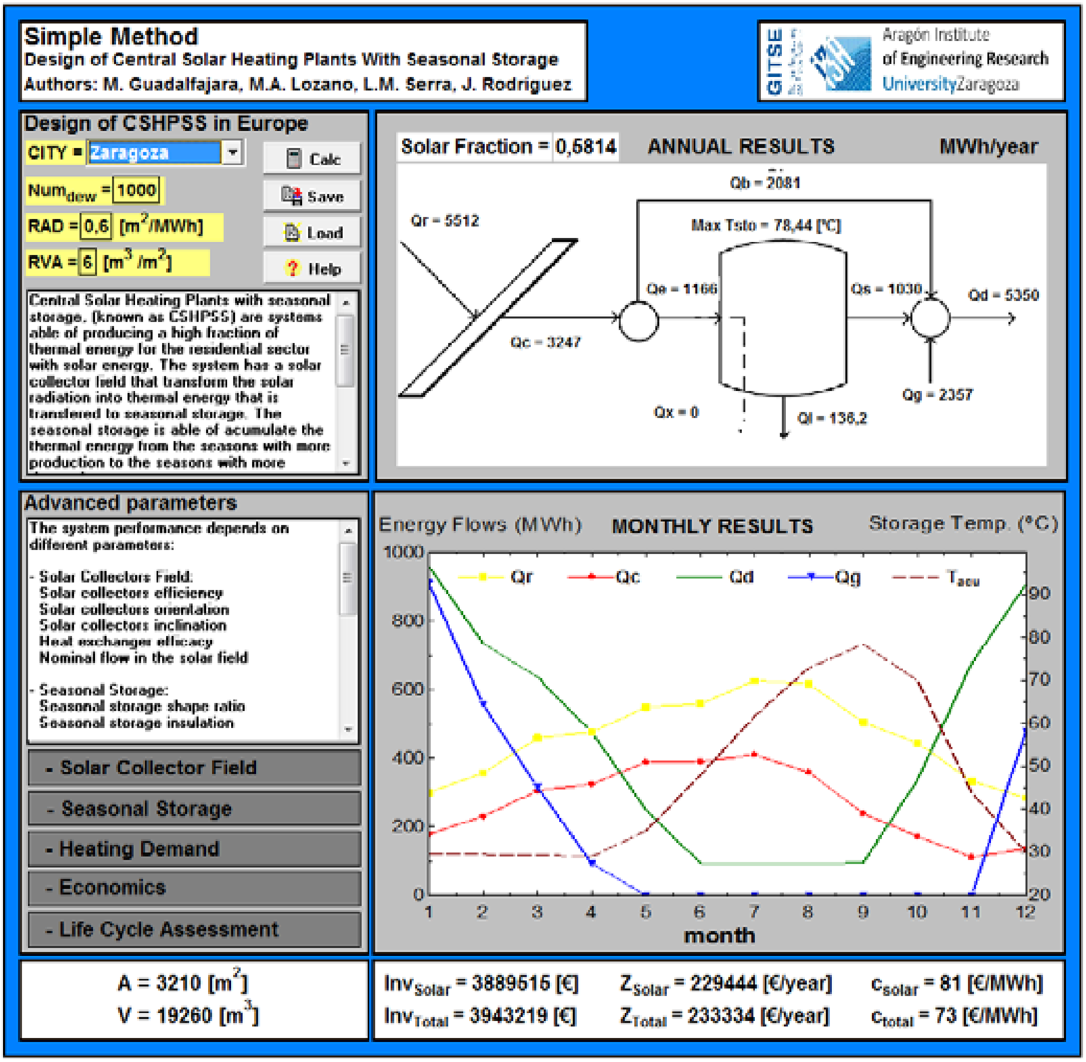

Fig. 1: Main window of the developed software for the analysis and evaluation of CSHPSS.

In the block on the left and top, the user can select the location for the calculation of the system, the number of dwellings and two main design parameters of the installation: RAD, Ratio Area of solar collector per unit of Demand, and RVA, Ratio of Volume of seasonal thermal energy storage per Area of solar collector. For each location is required to know the following climatic data: latitude; monthly daily average horizontal radiation; minimum, average and maximum temperatures of a typical day each month; and the European Heating Index (Werner, 2006). Nevertheless it is possible to add user defined locations, by selecting the option "New City" and introducing the corresponding climatic and demand data. In respect to the number of dwellings, it is recommended to select a value between 100 and 10,000. Regarding RAD, its value usually stays in a range between 0.1 and 5 $m^2/(MWh/yr)$; and in the case of RVA, the recommended interval is 0.5 and 10 m^3/m^2. Each design generated can be calculated pressing the button "Calc". Further it can be saved and loaded for future evaluations. On the right side is shown a diagram of the CSHPSS system containing the annual energy balance of the system as well as a chart with the monthly results for the main energy flows: incident solar radiation Q_r, solar heat collected Q_c, heating demand Q_d, auxiliary energy required Q_g; and seasonal storage temperature T_{acu}. On the bottom are shown the main sizing results, i.e. the area of solar collectors and the volume of the seasonal thermal energy storage. Furthermore is also presented an estimation of the investment required, cost of the solar thermal energy produced and cost of the total energy produced. Energy results are presented in MWh/year as general nomenclature. From this main window it can be accessed to the other windows of the software: Solar Collector Field, Seasonal Storage, Heating Demand, Economics and Life Cycle Assessment.

Results obtained for a designed system located in Zaragoza (Spain) consisting of 1000 dwellings of 100 m^2 each with design ratios RAD = 0.6 $m^2/(MWh/yr)$ and RVA = 6 m^3/m^2 are shown in Fig. 1. It can be noticed that the seasonal storage reaches a maximum temperature of 82 ºC which is lower than the maximum temperature permitted (90ºC), indicating that the seasonal storage is oversized. Calculating with RVA = 4 the storage reaches the maximum temperature but the obtained system has to reject part of the production in Summer, Q_x = 122 MWh/year. Following an iterative process the ratio RVA allowing to store all the summer production without heat rejection and avoiding the oversize of the tank can be obtained.

2.2. Solar Collector Field

The features of the solar collector field can be adjusted by the user in a specific window, see Fig. 2. The coefficients of performance of a commercial large flat plate solar collector (Arcon HT-SA 28/10) are implemented by default in the software and are shown in this window, but specific user defined values can be used. The solar collectors are considered by default oriented to the south (North hemisphere) and tilted with an inclination equal to the latitude, but deviations from this orientation and inclination can be used. The ground reflectance considered by default is 0.2. The specific heat capacity and density of the solar field fluid and the solar field flow per area of solar collector can also be adjusted. It is considered a heat exchanger, between the primary loop and the secondary loop feeding the seasonal storage tank, which effectiveness can also be user defined. By default water is considered as the working fluid in the solar field with a specific flow of 20 (kg/h)/m^2 and the heat exchanger effectiveness is 90%.

The monthly performance of the solar collector field is shown in a chart in which the incident solar radiation Q_r, solar heat collected Q_c, solar collector field efficiency η_{sf}, and solar fraction SF, are depicted (see Fig. 2). For the analyzed case, the solar collector field has a monthly efficiency between 70% and 35%. Note that the efficiency of the solar collectors is lower at the end of the charging season due to the high temperature in the seasonal storage tank.

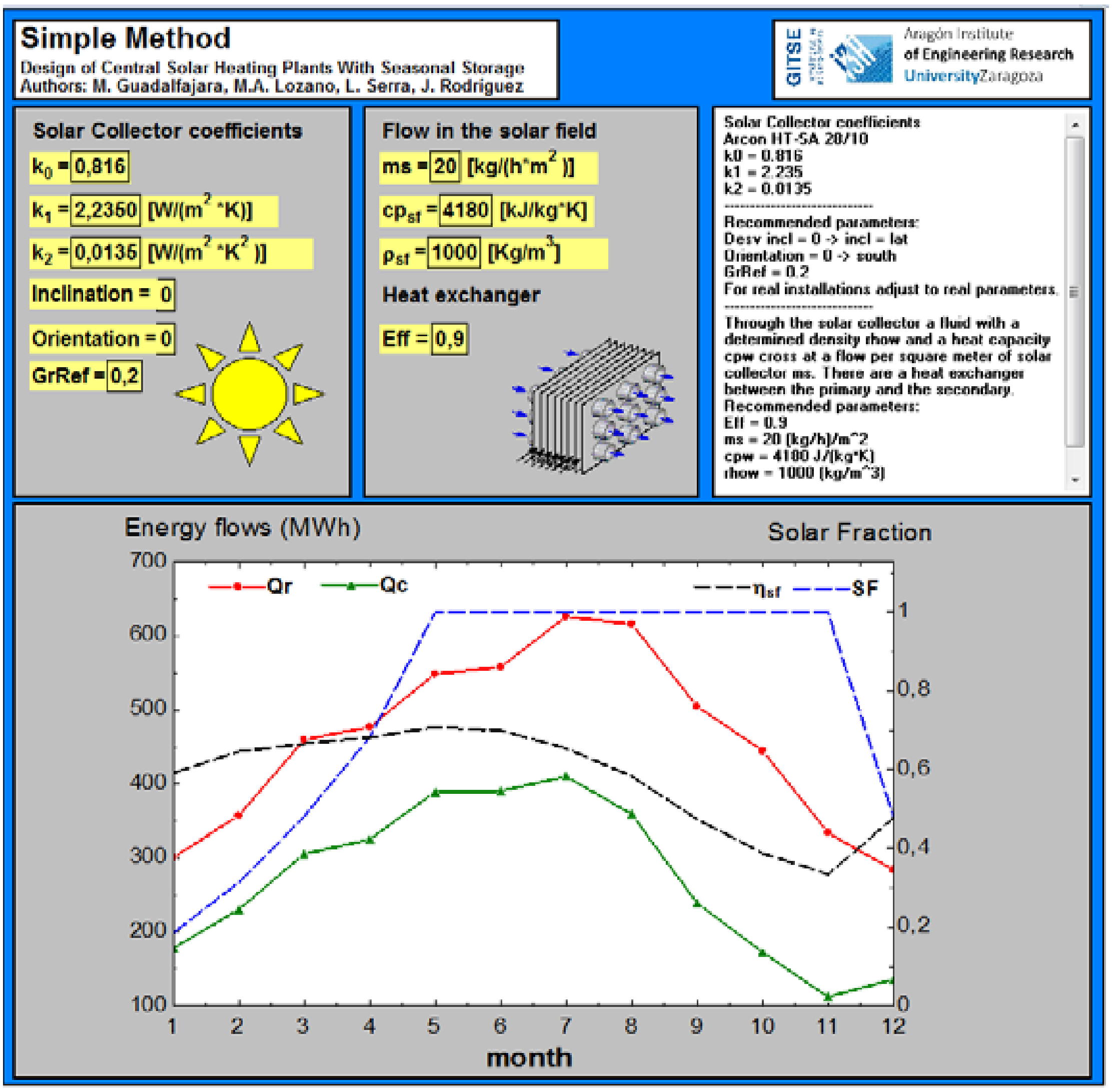

Fig. 2: Solar Collector field window of the developed software for the analysis and evaluation of CSHPSS.

2.3. Seasonal Storage

The seasonal thermal energy storage considered is a hot water tank. Its volume has already been determined with the design parameters RAD and RVA defined in the main window. More specific parameters of the thermal energy storage are set in this window. The shape of the thermal energy storage affects to the thermal energy transferred to the ambient. A cylindrical thermal energy storage tank is considered and the aspect of the tank (height divided by diameter) can be selected. The minimum default seasonal storage temperature of the CSHPSS plant connected to a low temperature district heating system is 30ºC but other minimum temperature values can be given if the designer considers different design restrictions. Similarly, the maximum default storage temperature considered is 90ºC but different maximum storage temperatures can also be used. The seasonal thermal energy storage tank has thermal losses to the environment through the storage envelope. A default value of the heat transfer coefficient of 0.12 W/(m^2·K) has been estimated, which can also be adjusted by the user. Further, the substance considered by default for thermal energy storage is water, however different substances, e.g. soil or gravel-water mixtures can be considered by implementing the corresponding heat capacity and density of the considered substance.

On the lower part of this window (see Fig. 3) are presented the main energy flows of the seasonal thermal energy storage: thermal losses Q_l, heat discharged Q_s, and heat rejected when the storage tank is fully charged Q_x. It is also shown the average temperature of the water in the seasonal storage tank (temperature stratification is not considered).

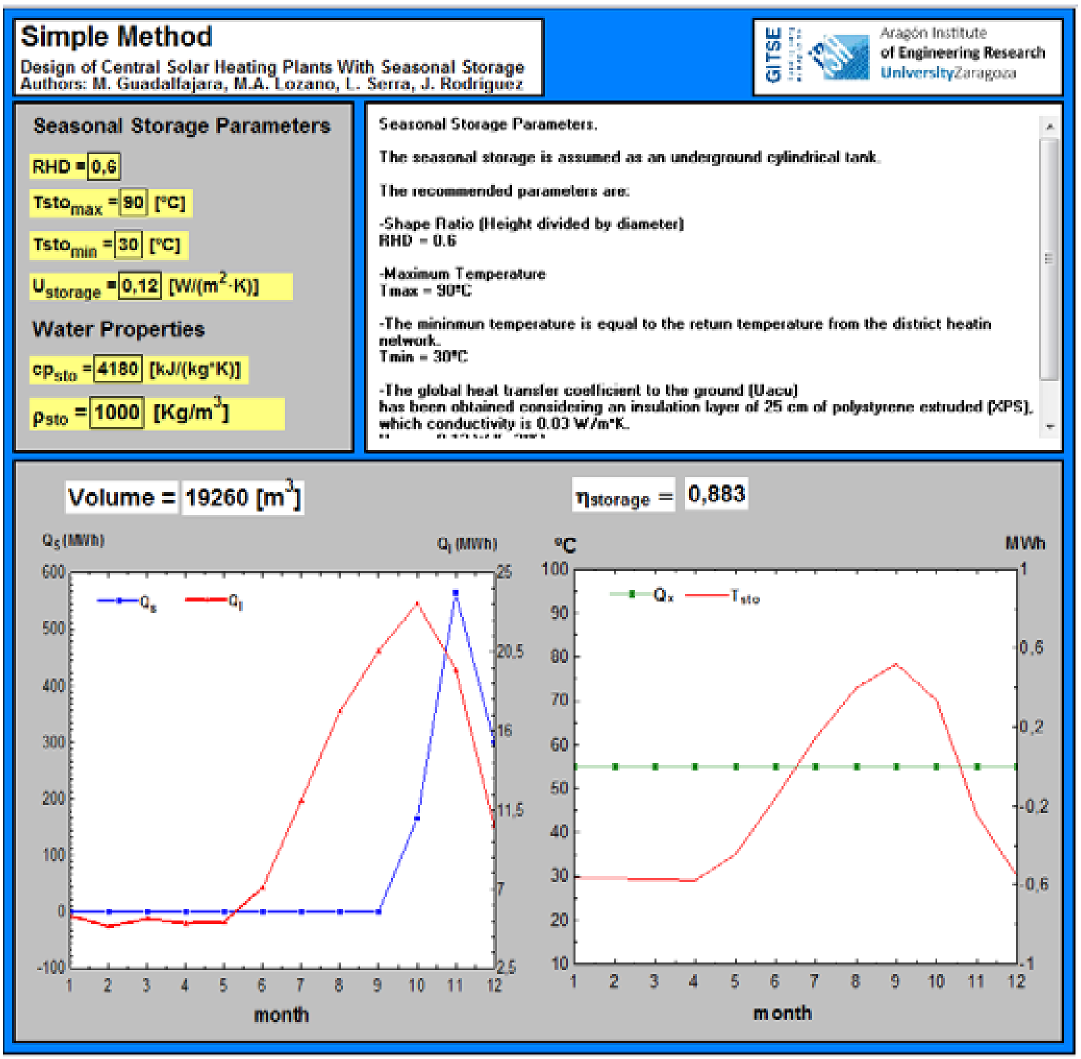

Fig. 3: Seasonal Storage window of the developed software for the analysis and evaluation of CSHPSS.

2.4. Heating Demand

The heating demand is calculated according to the number of dwellings, the dwelling size, and the average consumption of thermal energy per square meter. The size of the dwelling is 100 m^2 but it can be adjusted by the user as a design parameter.

The base annual space heating demand 43.2 kWh/m^2 (Guadalfajara et al., 2014c) is taken for new multifamily buildings in Madrid (Spain). Space heating (SH) demand for others locations in Europe has been obtained applying the European Heating Index (Werner, 2006). The space heating demand is distributed monthly according to the degree-days method. Erbs et al. (1983) correlation for degree-days is used to calculate monthly degree-days, and the user can select the base temperature. The user can modify the distribution of the thermal energy demand by changing the selected base temperature. Typical values used are 18 for regular buildings and 15 for efficient buildings, but other user defined values can be applied.

The consumption of thermal energy for the production of domestic hot water (DHW) depends on the size of the community, average consumption of DHW, occupation of the houses and temperature difference between supply water and hot water consumption temperature, 60ºC. An average consumption of 30 l/(person·day) and an occupancy of 40 m^2 per person are considered. Consult Guadalfajara et al. (2014c) for further details.

In the lower part of the window (see Fig. 4) are shown the monthly distribution of the domestic hot water demand $Q_{d,DHW}$, space heating demand $Q_{d,SH}$ and the total heating demand Q_d, as well as the average ambient temperature.

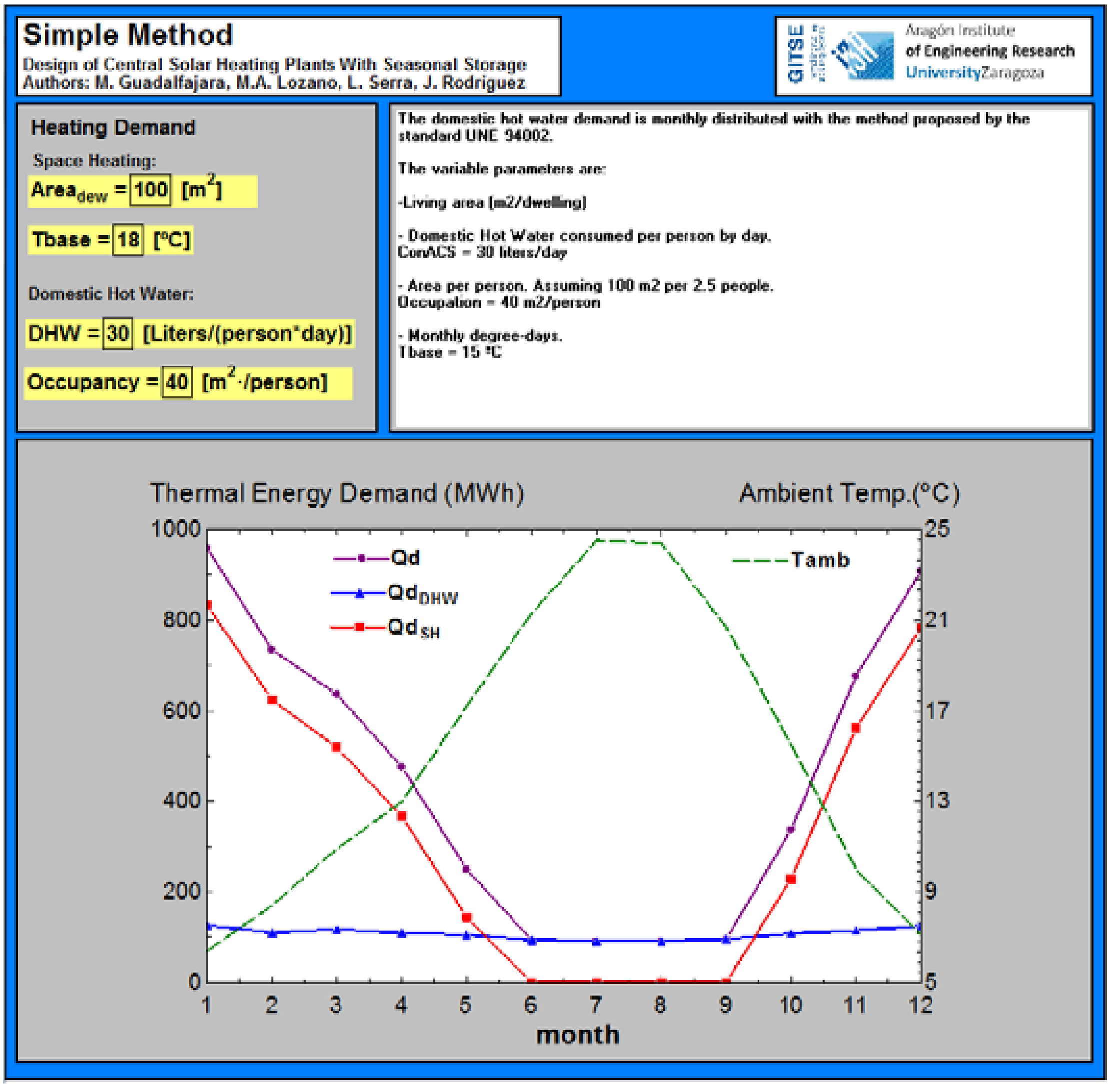

Fig. 4: Heating Demand window of the developed software for the analysis and evaluation of CSHPSS.

2.5. Economic evaluation

The developed software estimates the investment costs of the analyzed CSHPSS system and its operation costs corresponding to the electricity and the auxiliary energy consumed respectively by the pumps of the CSHPSS and by the auxiliary boilers required to cover the demand (Guadalfajara et al., 2014a). The prices of the electricity and the auxiliary energy source for heating are input values through the user interface (see Fig. 5), as well as the efficiency of the auxiliary boilers that can be given by the user.

The parameter α included as input data in the user interface is proposed to consider the economic costs of different technologies of thermal energy storage or the expected future price reduction associated to the technology development (Hadorn and Chuard, 1983; Boysen and Chant, 1986; De Wit, 2007; Ellehauge and Pedersen, 2007; Schmidt and Mangold, 2009). The value α = 1 corresponds with the experience gained in the demonstration projects of the two last decades using a hot water tank for thermal energy storage. The amortization factor is calculated considering an annual interest rate (i = 0.030 $year^{-1}$), which is an input value to the software. The amortization costs are distributed along the equipment lifetime (25 years for the solar collector and 50 years for the seasonal storage). The annual operation and maintenance costs are estimated as 1.5% (f_{ope} = 0.015 $year^{-1}$) of the investment cost according to the criteria proposed by the IEA (2012).

In the example illustrating this paper (see Fig. 5) the auxiliary energy system consists of a gas boiler with an average efficiency of 95%. Natural gas price is 58.3 €/MWh (Spanish gas price for commercial consumers). The price of the electricity consumed by the pumps is 166.5 €/MWh. The software provides an estimate of the investment costs of the solar system (with more detailed information for the main components –solar field and thermal energy storage), as well as the total costs including separately the cost of the solar heat and the cost of the auxiliary heat. A sensitivity analysis is also presented in a chart considering different values of annual interest rate for the investment costs.

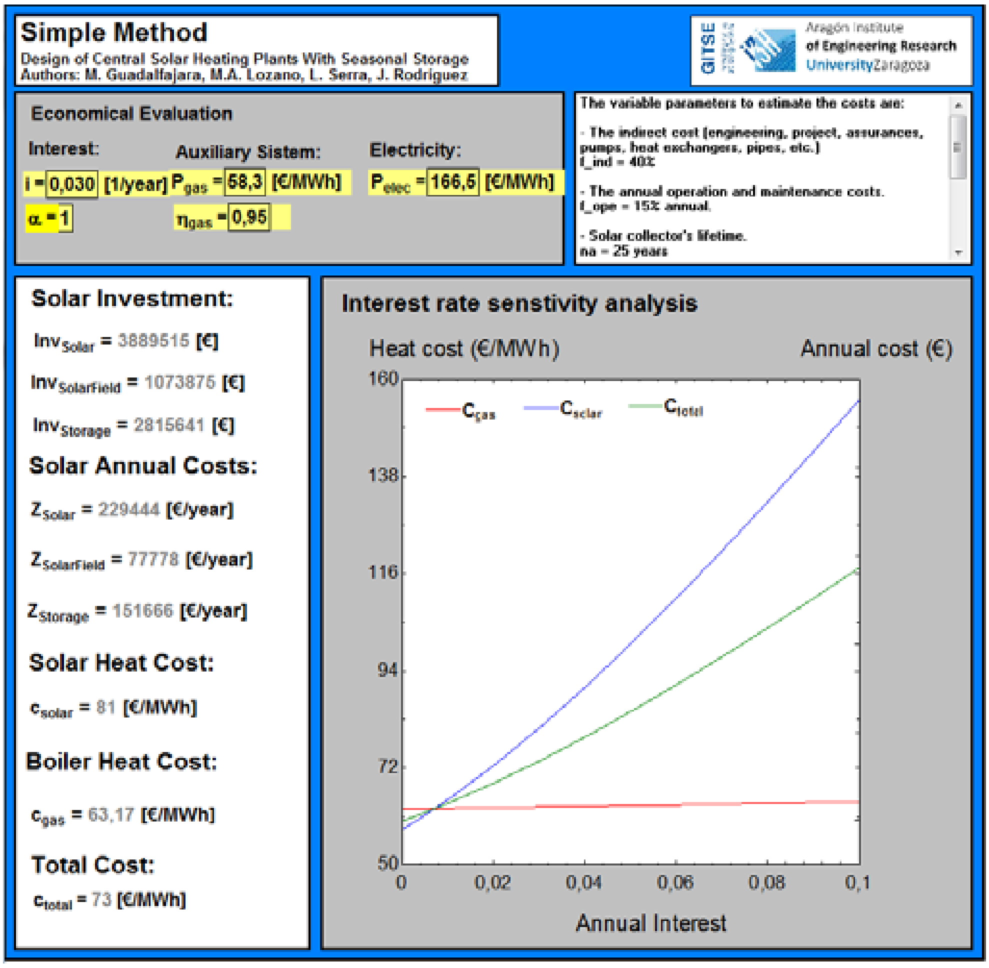

Fig. 5: Economic evaluation window of the developed software for the analysis and evaluation of CSHPSS.

2.6. Environmental assessment

There is also a specific window (see Fig. 6) providing an environmental assessment of the analyzed CSHPSS system based on the Life Cycle Assessment (LCA) methodology (Guinée, 2002). The software provides the greenhouse gas emissions of the system expressed in kg of CO_2 equivalent per MWh of heat produced and the primary energy consumption expressed in MWh of primary energy consumed per MWh of heat produced. In both cases the software evaluates the greenhouse gas emissions and the primary energy consumption associated to the equipment as well as to the operation (greenhouse gas emissions and the primary energy consumption associated to the consumption of electricity and auxiliary fuel during the operation).

The user can provide values of CO_2 equivalent emissions and primary energy consumption corresponding to the electricity and to the auxiliary fuel. By default the values implemented in the software are the Spanish conversion factors for the electricity and natural gas corresponding to the year 2011 (IDAE, 2014). These factors allow the evaluation of CO_2 equivalent emissions and the primary energy required associated to the operation of the system. The CO_2 equivalent emissions of each piece of equipment has been evaluated applying the LCA considering the IPCC 2007 method (PréConsultants, 2013) that uses the up-to-date figures of the Intergovernmental Panel on Climate Change (IPCC, 2007). Also the primary energy consumption associated to each piece of equipment is evaluated applying the Cumulative Energy Demand method (Huijbregts et al., 2010).

A detailed description of the procedure applied for the environmental assessment of a CSHPSS applying the Life Cycle Assessment technique can be found in the work of Raluy et al. (2014).

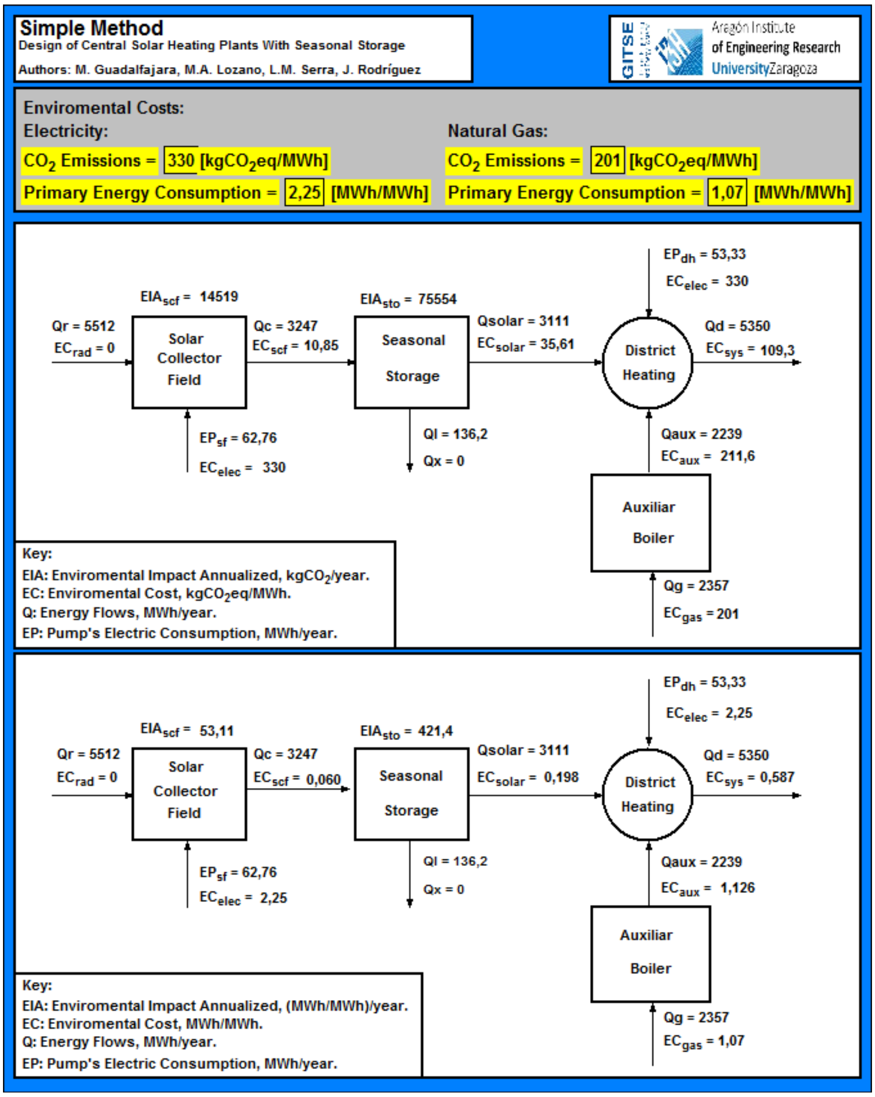

Fig. 6: Environmental assessment window of the developed software for the analysis and evaluation of CSHPSS.

3. Geographic analysis

For eight locations in Europe have been designed CSHPSS to cover the demand of space heating and domestic hot water for 1000 dwellings of 100 m^2 with a solar fraction of 50%. The systems fulfill the critical volume condition: accumulation of all the solar thermal energy produced in summer reaching the maximum storage temperature but without rejecting some heat. Climatic, demand and design parameters considered in the software as well as final results obtained are presented in Table 1. Locations with higher radiation require a lower ratio RAD to obtain the same solar fraction. The radiation is higher and also the efficiency of the solar collectors.

Table. 1: Climatic data, design data and results for different locations in Europe, 50% solar fraction, 1000 dwellings, 100m²

City	Radiation kWh/(m^2·day)	Q_d MWh/yr	RAD m^2/MWh	RVA m^3/m^2	A m^2	V m^3	η_{coll} (%)	η_{acu} (%)	η_{sys} (%)
Athens	4.92	4564	0.45	5.08	2,054	10,434	58.3 %	87.0 %	55.8 %
Rome	4.36	5105	0.52	4.85	2,655	12,877	56.7 %	87.7 %	54.2 %
Madrid	4.51	5815	0.49	4.84	2,849	13,791	58.4 %	88.7 %	56.1 %
Paris	2.82	6279	1.02	2.41	6,405	15,437	46.0 %	88.0 %	44.1 %
Berlin	2.87	6817	0.97	2.58	6,613	17,062	46.1 %	87.8 %	44.1 %
Riga	2.71	7476	1.19	2.41	8,897	21,443	41.3 %	87.3 %	39.1 %
Oslo	2.43	8084	1.39	1.75	11,237	19,665	37.8 %	86.8 %	36.1 %
Umea	2.44	8412	1.10	1.37	9,254	12,678	41.9 %	85.4 %	40.5 %

Oslo, Berlin and Madrid are cities in Europe with different design conditions due to climate and demand. It is important to note that obtaining the same solar fraction requires very different sizing of the solar collector field and the seasonal storage. In Figure 7 is depicted the area of solar collectors and the volume of seasonal storage required to obtain a specified solar fraction with the design criteria of critical volume. Relevant conclusions about the effect of the location on the design of these systems can be obtained from this graph. For same size communities to obtain the same solar fraction it is required a larger area of solar collector in cold climates than in warm climates and the volume of seasonal storage required per area of solar collector is very different for each climate, not lineal relation between those factors.

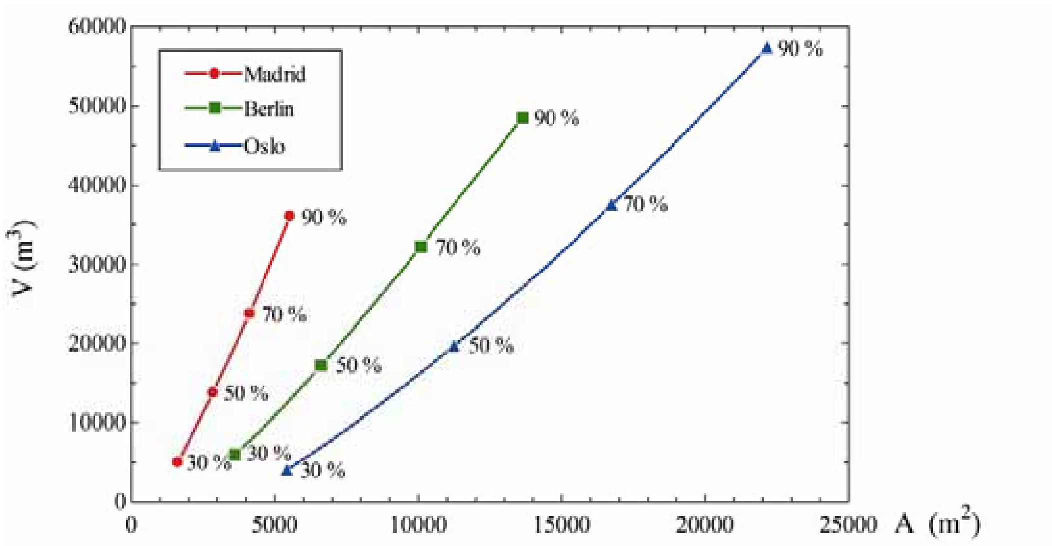

Fig. 7: Design parameters for different solar fraction in different climates in Europe, 1000 dwellings of 100 m².

4. Conclusions

A software for the analysis, pre-design and performance evaluation of CSHPSS, based on a simple calculation method developed by the authors (Guadalfajara et al., 2014a) has been presented. The distributable program, currently as a beta version, has been built with the Engineering Equation Software (EES, 2013). Using demand data and public climatic data that can be easily obtained, the software calculates the annual behavior of a CSHPSS plant on a monthly basis.

The developed software consists of four sequential modules for the calculation of the annual and monthly performance of a CSHPSS system. The Module 1 elaborates the hourly and monthly climatic and demand data required to calculate the system performance (hourly radiation on tilted surface, hourly ambient temperature, monthly demand…). The Module 2 calculates the monthly production of the solar field based on the hourly incident radiation and hourly ambient temperature of a typical day for each month, and on the storage tank temperature at the beginning of the considered month. The Module 3 calculates the monthly values of the energy charged/discharged/accumulated in the seasonal storage tank and the auxiliary energy (if required), as well as the final temperature of the water in the tank and the heat rejected (in case the storage tank would be fully charged). And the Module 4 calculates the results (monthly and annual energy balance, efficiency of solar field, and solar fraction; annual efficiency of thermal energy storage and global efficiency of the system), estimation of the investment, operation and maintenance costs. Finally the unit economic cost, CO_2 equivalent emissions and primary energy for solar heat are obtained.

A user friendly interface consisting of six windows has been built, starting from general parameters of the system (main window) to specific considerations of each component (solar collector field, seasonal storage and heating demand) as well as to the economic and environmental information for economic and environmental evaluations. Through these windows the design parameters can be defined and the results are presented with the help of several graphs and diagrams that support the evaluation of CSHPSS.

As a result, with the developed software can be, easily and quickly, obtained technical, economic and environmental results about the system performance. The software generates an estimation of the economic and environmental solar heat cost, as well as preliminary values of the main design parameters of the CSHPSS system (solar field area and volume of the seasonal thermal energy storage). The design and evaluation of CSHPSS for different cities in Europe were performed obtaining relevant conclusions about the geographic variation of design requirements.

5. Acknowledgements

The present results have been developed in the frame of the research project ENE 2010-19346, partially funded by the Spanish Goverment (ENERGY research program), the Government of Aragon and the Social EU Fund (FEDER Program).

6. References

ARCON. Arcon HT-SA 28/10. http://www.arcon.dk [accessed: February 2013].

Boysen, A., Chant, P., 1986. Summary report of phases I and II. IEA SHC Task 7: Central solar heating plants with seasonal storage. http://task07.iea-shc.org/publications [accessed: August 2014].

Braun, J.E., Klein S.A., Mitchell, J.W., 1981. Seasonal Storage of Energy in solar heating. Solar Energy. 26, 403-411.

CTE, 2006. Código Técnico de la Edificación. Documento Básico de Ahorro de Energía, Contribución Solar Mínima de Agua Caliente Sanitaria, DB-HE4. Real Decreto 314/2006 Spanish Government

De Wit, J., 2007. Heat storages for CHP optimization. PowerGen Europe 2007. Paper ID-94.

EES, 2013. Engineering Equation Solver. F-Chart Software.

Ellehauge, K., Pedersen, T.E., 2007. Solar heat storages in district heating networks. Energienet.dk, PREHEAT project nº 2006-2-6750.

Erbs, D.G., Klein, S.A., Beckman, W.A., 1983. Estimation of degree-days and ambient temperature bin data from monthly-average temperature. ASHRAE Journal. 25(6), 60-65.

Guadalfajara, M., Lozano, M.A., Serra, L.M., 2012. Evaluation of the Potential of Large Solar Heating Plants in Spain. Energy Procedia. 30, 838-848.

Guadalfajara, M., 2013. Evaluación de centrales solares térmicas para el sector residencial en España. Master Thesis, EINA, Universidad de Zaragoza.

Guadalfajara, M., Lozano, M.A., Serra, L.M., 2014a. A simple method to calculate Central Solar Heating Plants with Seasonal Storage. Energy Procedia. 48, 1096-1109.

Guadalfajara, M., Lozano, M.A., Serra, L.M., 2014b. Comparison of simple methods for the design of central solar heating plants with seasonal storage. Energy Procedia. 48, 1110-1117.

Guadalfajara, M., Lozano, M.A., Serra, L.M., 2014c. Geographical evaluation of Central Solar Heating Plants with Seasonal Storage for the residential sector in Europe. The 14th International Symposium on District Heating and Cooling, Stockholm, Sweden.

Guinée, J.B. (Ed.), 2002. Handbook on Life Cycle Assessment: Operation Guide to the ISO Standards. Kluwer Academic Pubs., Dordrecht.

Hadorn, J.C., Chuard, P., 1983. Cost data and cost equations for heat storage concepts. IEA SHC Task 7: Central solar heating plants with seasonal storage. http://task07.iea-shc.org/publications [accessed: August 2014].

Huijbregts, M.A.J., Hellweg, S., Frishknecht, R., Hendriks, H.W.M., Hungebuhler, K., Hendriks, A.J. Cumulative Energy Demand as a predictor for the environmental burden of commodity production. Environmental Science &Technology. 44(6), 2189-2196.

IDAE 2014 Factores de conversion energía final-energía primaria y factores de emisión de CO2 – 2011 http://www.idae.es/uploads/documentos/documentos_Factores_Conversion_Energia_y_CO2_2011_0a9cb73 4.pdf [Accessed June 2014].

IEA, 2012. Technology Roadmap Solar Heating and Cooling. International Energy Agency. Paris.

IEA, 2013. Key World EnergyStatistics 2012. International Energy Agency. Paris.

IPCC, Intergovernmental Panel on Climate Change, 2007. Fourth Assessment Report of the IPCC. The physical science basis. Cambridge University Press, Cambridge (UK) and New York (USA).

Lozano, M.A., Anastasia, A., Palacín, F., Serra, L.M., 2010. Simulation study and economic analysis of large scales solar heating plants in Spain. Eurosun 2010, Graz, Austria.

Lunde, P.J., 1979. Prediction of the performance of solar heating systems utilizing annual storage. Solar Energy. 22, 69-75.

Lundh, M., Dalenbäck, J.O., 2008. Swedish solar heated residential area with seasonal storage in rock: Initial evaluation. Renewable Energy. 33, 703-711.

Pré Consultants, 2013. SimaPro 8. Database Manual. Methods library. The Netherlands.

Raab, S., Mangold, D., Müller-Steinhagen, H., 2005. Validation of a computer model for solar assisted district heating systems with seasonal hot water heat store. Solar Energy. 79, 531-543.

Raluy, R.G., Serra, L.M., Guadalfajara, M., Lozano, M.A., 2014. Life Cycle Assessment (LCA) of Central Solar Heating Plants with Seasonal Storage (CSHPSS). Energy Procedia. 48, 966-976.

Schmidt, T., Mangold, D. 2009. Status of Solar Thermal Seasonal Storage in Germany. Effstock 2009, Stockholm, Sweden.

TRNSYS 16, 2004. A Transient System Simulation tool. SEL, University of Wisconsin-Madison.

Werner, S., 2006. The new European Heating Index. 10th International Symposium on District Heating and Cooling, September 3-5, Hannover, Germany.