Modeling an Energy Storage System Based on a Hybrid Renewable Energy System in Stand-alone Applications

ALEXANDRU CIOCAN[1,2,3]*, OVIDIU MIHAI BALAN[1], MIHAELA RAMONA BUGA[1], TUDOR PRISECARU[2], MOHAND TAZEROUT[3]
[1]National R&D Institute for Cryogenic and Isotopic Technologies ICIT Rm. Valcea, 4 Uzinei Str., 240050, Rm. Valcea, Romania
[2]University Politehnicaof Bucharest, Faculty of Mechanical Engineering and Mechatronics, 313 Spl. Independentei, 060042, Bucharest, Romania
[3]Ecole des Mines de Nantes, 2 Rue Alfred Kastler, 44300 Nantes, France

The current paper presents an energy storage system that stores the excessive energy, provided by a hybrid system of renewable energy sources, in the form of compressed air and thermal heat. Using energy storage systems together with renewable energy sources represents a major challenge that could ensure the transition to a viable economic future and a decarbonized economy. Thermodynamic calculations are conducted to investigate the performance of such systems by using Matlab simulation tools. The results indicate the values of primary and global efficiencies for various operating scenarios for the energy storage systems which use compressed air as medium storage, and shows that these could be very effective systems, proving the possibility to supply to the final user three types of energy: electricity, heat and cold function of his needs.

Keywords: renewable energy, compressed air energy storage, thermal energy storage, trigeneration, thermodynamic analysis

During the years, renewable energy has presented two main characteristics which make them ideal for energy source production, being inexhaustible sources and friendly with the environment as long as are not polluting or producing waste materials.

However there are some issues that must be solved in the field of renewable energy, particularly solar and wind energy are intermittent, their behavior varies not only hourly, but daily or weekly as well, the fact that makes them not be always available when are needed. In order to valorize the excess of renewable electricity with their intermittent nature, to match energy supply with demand, to avoid the non-optimal use of renewable energy sources and loss of value and to increase the grid stability, if the system is connected to it, energy storage solutions are required.

There are several energy storage solutions worldwide including pumped hydro storage, flywheels, batteries, hydrogen storage, compressed air energy storage (CAES) and maybe others. Some of them showed their impact in large scale storage and other in small scale applications [1-6].

Experimental part

Method - Proposed configuration of the system

The system analyzed in this paper consists of wind turbines which can be placed both on-shore and off-shore, a concentrated solar power (dish Stirling engine) and a storage energy system in the form of compressed air.

This kind of systems which involves compressed air energy storage, represented in figures 1 and 2, can be used for both large and small-scale storage, however, the model has been tested for a small scale application. One of the benefits of energy storage in the form of compressed air is given by the fact that the system is able to supply to the consumer three types of energy: electricity, heat, and cold or only electricity, depending on his needs.

In figure 1*M* is the electric engine, *HPC* and *LPC* are the high-pressure compressor respectively the low-pressure compressor, *HEs* are the heat exchangers, *HTF* is the heat transfer fluid, *Pump* is the recirculating pump for the *HTF*, where the route of the cold *HTF* has been highlighted with dashed line while with simple line has been highlighted the route of the hot *HTF*, *HPT* and *LPT* are the high-pressure

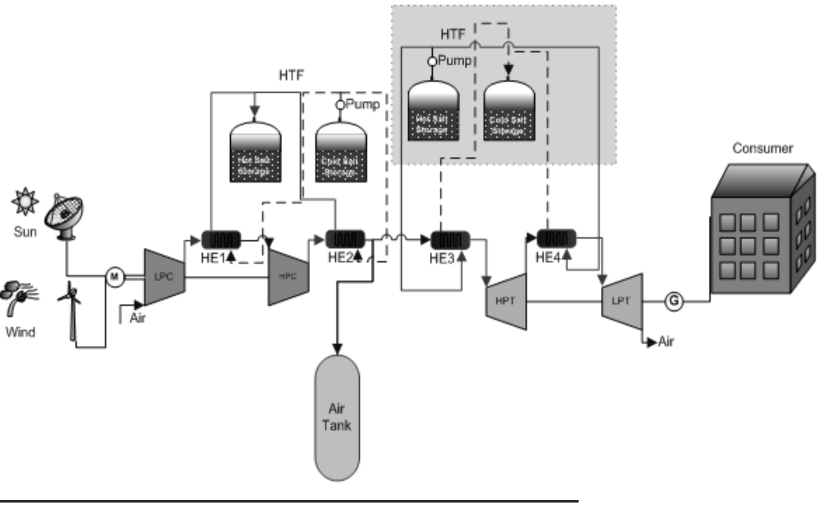

Fig. 1. Scheme of an adiabatic compressed air energy storage system (A-CAES)

---

* *email: alexandru.ciocan@icsi.ro*

turbine respectively low-pressure turbine and *G* is the electric generator.

The working principle of the system presented in figure 1 is that if there is a surplus of energy provided by renewable energy sources (wind or sun) a multi-stage compressor is used to compress the air and to store it into a storage vessel. After each compression stage, the heat resulted is recovered through the heat exchangers and two tanks, one cold one hot, and stored for further use. When there is a demand for energy a multi-stage expander connected to a generator is used to supply electricity to the consumer. During the expansion process, the heat stored could be used to re-heat the air and to increase the primary efficiency of the system.

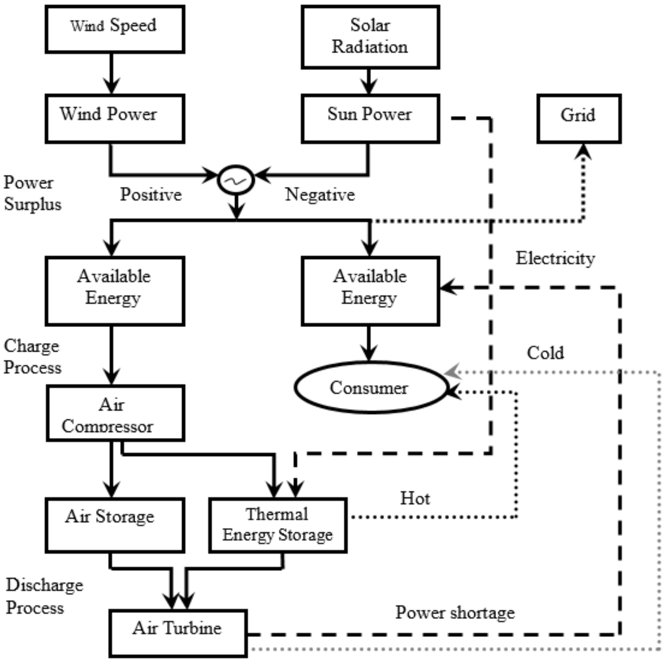

Fig. 2. The block diagram for a hybrid system which involves: renewable energy sources, energy storage in the form of compressed air and thermal energy storage in the form of sensible heat [7]

Wind turbines

Wind energy is recognized as the most economically competitive energy and it plays an important role both in the diversification of energy system and also in greenhouse gas emissions. As long as wind turbines are available in a very large range of size starting from watts to megawatts this makes them usable for both householders and business. Wind turbines work by converting the kinetic energy of the wind first in the rotational kinetic energy in turbine and then in electrical energy that can be supplied for the final purpose.

Photovoltaic panels and Concentrated Solar Power (CSP)

The use of photovoltaic cells is the most mature technology used to transform solar radiation into electricity throughout the photoelectric effect. Another technology which is frequently used in our days is by using solar radiation to heat water capable to run a steam turbine to produce electricity.

The less mature technology and with a huge potential involves solar concentrators in various forms: parabolic trough collectors, power towers with central receiver systems, linear Fresnel reflectors and dish Stirling engine. The working principle of a CSP system is based on a thermal power plant cycle, where solar radiation is converted to heat to obtain superheated stream. In the proposed configuration the CSP is made of a dish solar collector equipped with a Stirling engine.

Compressed air energy storage

In a CAES system electricity is used to compress air during off-peak hours or when is an excess of energy from intermittent sources, stored in the form of compressed air in underground, underwater or above ground containers and re-used during on-peak hours or in periods when there is no other source of energy. Conventional CAES systems use fossil fuel, which produces greenhouse gasses emissions (GHG), to increase the expanded air temperature, however, in this paper, our attention is focused on a compressed air energy storage system where the heat resulted during the compression process is re-used during the expansion process.

It is well known that a compressed air energy storage system can operate in three ways when is used to produce electricity. The first scenario is at variable inlet turbine pressure which varies with the storage vessel pressure, the second scenario is at a constant inlet turbine pressure by throttling the upstream air to a fixed pressure and the third scenario is by maintaining a constant pressure during the air expansion by using methods which allow this [8-16]. According to the reference [1-2], a scenario where the air is compressed at constant pressure and expanded from constant pressure following a reversible process has the highest possible efficiency. However, this solution is limited by the storage vessel construction. In reference [3] there are solutions which present underwater bags used to store pressurized air by using the hydrostatic pressure of the water (ocean, sea) to maintain the constant pressure during each process either compression or expansion.

Energy storage in the form of compressed air can be viewed in a simple way as two different processes, one is the charging process when the air is taken from the atmosphere, compressed and stored in a storage vessel when there is a surplus of renewable energy. Later when there is not enough energy to satisfy the consumer needs an expander is used to produce electricity through the compressed air. A single-stage compression may results in relatively high temperature, for a high-pressure compressor built of materials that withstand high temperature involving a high cost. To avoid these costs and very high temperatures, multi-stage compressors are preferred. The heat resulted during compression process can be used for different purposes, as domestic water, for heating the buildings or can be stored to re-heat the air on the path between the storage vessel and the air turbine in order to increase the primary efficiency of the system.

The compression process

The energy consumed by compressor to compress the air is the amount of energy required for each compression stage. The equations follow the same rules whatever type of compressor is used: reciprocating, screw, scroll or vane [2, 14, 17]:

$$W_{polyt_{comp.}} = P_{\text{in}1}V_{\text{in}1}\frac{n}{n-1}\,\mathrm{x}$$

$$\mathrm{x}\left[\left(\frac{P_{out1}}{P_{\text{in}1}}\right)^{\frac{n-1}{n}}-1\right]+P_{\text{in}2}V_{\text{in}2}\frac{n}{n-1}\left[\left(\frac{P_{\text{out}2}}{P_{\text{in}2}}\right)^{\frac{n-1}{n}}-1\right]+$$

$$+P_{in3}V_{in3}\frac{n}{n-1}\left[\left(\frac{P_{out3}}{P_{in3}}\right)^{\frac{n-1}{n}}-1\right] \quad (1)$$

$$T_{out3} = T_{in3}\left(\frac{P_{out3}}{P_{in3}}\right)^{\frac{n-1}{n}} \quad (2)$$

$$Q = c_p^{air}\mathrm{m}_{air}\left(T_{in}^{air} - T_{out}^{air}\right) = \quad (3)$$

$$= c_p^{fluid}\mathrm{m}_{fluid}\left(T_{out}^{fluid} - T_{in}^{fluid}\right)$$

where $W_{polyt,comp.}$ is the energy consumed by compressor to compress the air in a polytropic process, P_{in}, P_{out} are the inlet and the outlet pressures, V_{in}, V_{out} are the inlet and the outlet volumes, index 1, 2 and 3 are the number of compression stages, should be mentioned that what goes out of a stage of compression enters to the next (e.g.: $P_{out1} = P_{in2}$) and so on, is assumed that there are no pressure loss, and **n** is the polytropic index. Even if in theory we report to an adiabatic compressor from the best knowledge of the authors such a compressor has not yet been built, so the obtained results are for a polytropic process.

After each stage compression, the air is cooled through a heat exchanger in counter-current. The heat resulted, Q, is stored in a thermal energy storage systems for further use. The index fluid in equation (3) represents the fluid used for thermal energy storage, while c_p is the specific heat capacity at constant pressure, m_{air} is the mass of the air stored and m_{fluid} is the mass of the working fluid used to recover the thermal energy, T_{in} and T_{out} are the inlet and the outlet temperatures for both fluids. In this work thermal energy storage in the form of sensible heat was preferred, molten salt, minerals oil, pressurized water could be considered as suitable solutions.

The expansion process

The energy resulted during the expansion process is the amount of energy obtained for each expansion stage.

The equation (4) shows the energy obtained for a single stage expansion [17].

$$W_{polyt\_engine} = m_{air}\frac{n}{n-1}RT_{in}\left[1-\left(\frac{P_{in}}{P_{out}}\right)^{\frac{n-1}{n}}\right] \quad (4)$$

$$n = \frac{\ln\left(\frac{P_{in}}{P_{out}}\right)}{\ln\left(\frac{P_{in}}{P_{out}}\right)-\ln\left(\frac{T_{in}}{T_{out}}\right)} \quad (5)$$

$$T_{out} = T_{in}\left(\frac{P_{out}}{P_{in}}\right)^{\frac{n-1}{n}} \quad (6)$$

where W_{polyt_engine} engine is the work done by the air engine, R is the specific gas constant, T_{in}, T_{out}, P_{in}, P_{out} are temperatures and pressures at the inlet respectively at the outlet of the air engine. The final temperature at the outlet of the air engine/turbine is given by the equation (6) [17]. In the case that the air is expanded from ambient temperature without preheating depending on the expansion pressure a significant amount of cold is resulted. For cold recovery during expansion process could be used the same equation, (3) as in the case of the compression process.

Results and discussions

As we mentioned before the model can be applied for both small and large scale storage. The experimental results were obtained on a laboratory stand which includes a multi-stage compressor at 300 bar, a storage vessel – steel tank 0.3 m^3, and a radial air engine with a maximum 8 bar inlet pressure.

Figure 3 and figure 4 present the temperature and pressure values after each compression stage. It can been seen that the 3rd stage compression has a different behavior comparing with the other two, due to the fact that if in the first two stages the discharging valves open at a constant value, the discharging valve of the 3rd compressor opens first at a constant pressure at a value about 170 bar then when the pressure into the storage vessel reaches this value then the discharging valve works function of differential pressure.

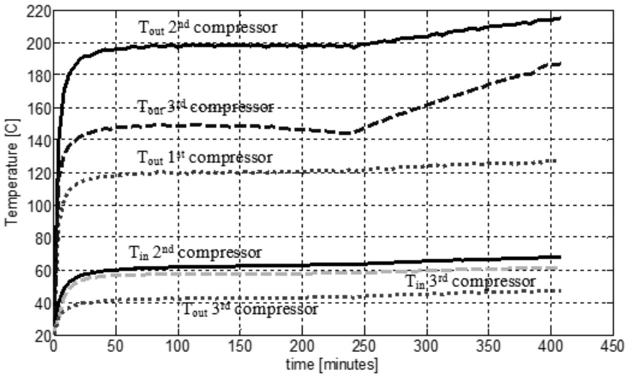

Fig. 3. Time variation in temperature at the outlet of each compression stage

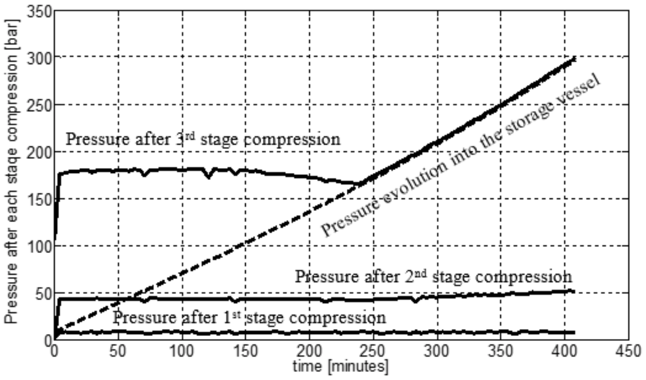

Fig. 4. Time variation in pressure at the outlet of each compression stage and into the storage vessel too

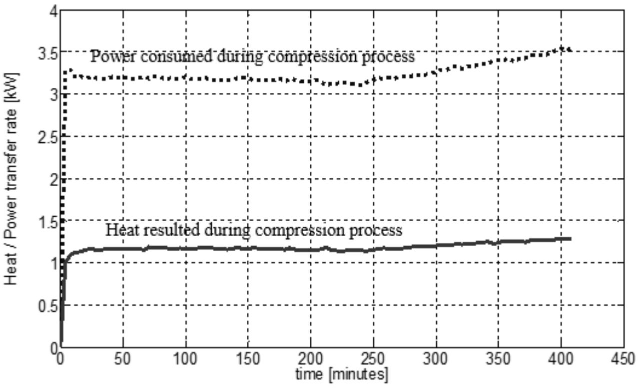

Fig. 5. Power consumed vs heat resulted during the air compression process

Figure 5 shows the energy consumed by the compressor and the heat resulted during the compression process. The two curves follow the same trend like the curve of pressure and temperature from figures 3 and 4.

Figure 6 presents the air temperature to the inlet and to the outlet of the air engine. The curve which represents the inlet temperature has at the beginning a descending trend and at one moment the temperature starts to increase. That happens due to the fact that once the compressed air is released from the storage vessel the air temperature into the reservoir start to decrease until the amount of air into the reservoir is small enough to be heated by surrounding.

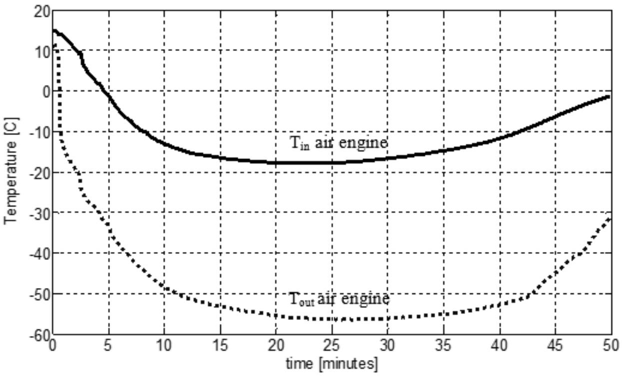

Fig. 6. Time variation in temperature at the inlet/outlet of the air engine

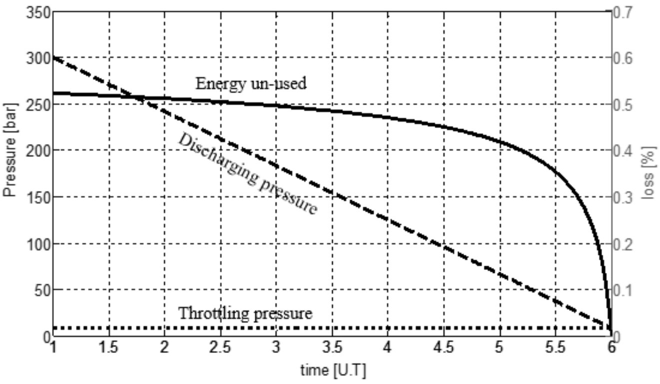

Fig. 7. Time variation in pressure into the storage vessel during discharging process and the ratio of energy un-used by throttling the upstream air

Figure 7 shows the energy un-used by throttling the upstream air. In the experimental set-up, this value has been seen to be close to the value of 45% due to the fact that the air is compressed at 300 bar and throttled for expansion from 8 bar (air engine limitations). Theoretical has been found that considering a storage vessel ratio no more than 2, then the value of energy un-used decrease suddenly to a value less than 10% and this value increases slowly once with the pressure from which the air is expanded.

Figure 8 presents the evolution of the power produced by the air engine during expansion process and the quantity of cold too, the last one was calculated having as reference the ambient temperature of 20°C.

The experimental results are not so encouraging showing that the compressor consumes 21.4 kWh of energy to fulfill a tank of 0.3 m^3 from 8 to 300 bar. During compression 8.1 kWh of thermal energy are dissipated into the environment. Meanwhile during expansion process for a complete discharge of the tank having the upstream pressure throttled at 8 bar are obtained 0.81 kWh of electricity and 1.1 kWh of cold, which means a primary system efficiency of 4.7% and a global efficiency of 46.7 %. However following a similarity criterion theoretical results show that decreasing the storage vessel ratio the system efficiency has a significant increasing.

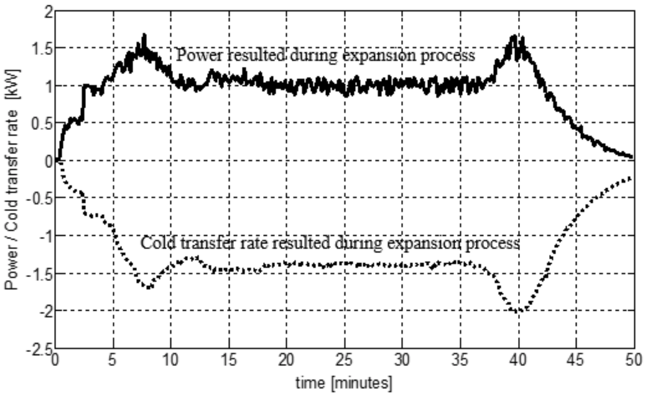

Fig. 8. Time variation in power during expansion process and the cold transfer rate calculated function of the outlet air engine temperature

Conclusions

The global efficiency of the system depends on the operating conditions. A theoretical efficiency close to 70% is possible only if the both processes are reversible by mean compression and expansion are done from the same pressure, solution possible if as storage containers are used underwater bags, or aquifers, and only if the air is re-heated with the heat recovered during the compression process.

The smaller the difference between the minimum and the maximum storage pressure into the storage vessel is than the greater primary efficiency system is. Taking into consideration scenarios in which the air is compressed to a pressure two times higher than the throttled pressure than a theoretical efficiency has been found of 52% and increase to 68% once with this ratio tends to 1, for scenarios in which the heat resulted in compression is returned to the air during expansion process. Efficiency between 37% to 51% has been found for scenarios in which the heat resulted in compression is used for other purposes.

However in the experimental set-up considering that our compressor was a 3 stage compression at 300 bars, storage vessel a stack of steel bottles, and our expander – a radial air engine with a maximum 8 bar air inlet pressure, the primary system efficiency without to re-heat the air before expansion has been proven to be very low only 4-5%, thing easily explained if we look at figure 7. Regarded to figure 7 can be seen that when a control valve is used to fix a constant pressure at the inlet of the expander in order to control the power supplied to the consumer everything happens inside the valve has as direct results energy un-used.

The presented results showed that this kind of systems are capable of supplying to the final user three types of energy depending on his needs. The way how the stored energy is handled depends by the economic assessment and the consumption predictions for electricity and heat.

Using a buffer volume of air into the storage tank helps significantly in reducing the temperature variation during the both processes compression and expansion. Sometimes this storage buffer involves a large storage vessel and if aboveground storage solutions are considered may not be a feasible one being required a large amount of raw material in order to build the storage vessel, unless if those are not already built, looking at salt caverns or depleted mines.

Though compressed air storage solutions could become economically viable there still are some issues that require to be solved. For small scale storage solutions without another storage systems like batteries or supercapacitors, to help compressor works is difficult to be used by the fact that commercial compressor hasn't been designed for use in energy storage purposes more than that used together with renewable sources. If the systems are not modular than the compressor will not start until the power generated by renewable sources doesn't meet the power required for compressor starts, which means that there is energy that cannot be stored. The same thing happens in the case of a higher power supplied by renewable sources, the power that exceeds the compressor power cannot be stored in the form of compressed air. So new designs for wind turbines and compressors are required in order to overcome this issues.

From an environmental point of view, is interested to observe that such a system which is able to supply energy in trigeneration could also provide environmental benefits, being *a clean* source of energy and playing an important role in integrating at a widely scale renewable energy sources.

References

1. SUCCAR S., DENKENBERGER C.D., WILLIAMS H.R., Applied Energy, **96**, 2012, p. 222-234

2. PIMM J. A., GARVERY D. S., DE JONG M., Energy**,** **66**, 2014, p. 496

3. KIM Y.M.,LEE J.H., KIM S.J., FAVRAT D., Entropy, **14**, 2012, p. 1501

4. BALAN, O.M., BUGA ,M.R., BILDEA, C.S., Rev. Chim.(Bucharest), **67,** no. 11, 2016, p. 2237

5. MAHILA T.M.I., SAKTISAHDAN T.J., JANNIFAR A., HASAN M.H., MATSEELAR H.S.C., Renewable and Sustainable Energy Reviews, **33**, 2014, p. 532

6. ZACH K., AUER H., LETTNER H., Report summarizing the current Status, Role and Costs of Energy Storage Technology, www.store-project.eu, 2012.

7. CIOCAN A., PRISECARU T., TAZEROUT M., DURASTANTI J.-F., Thermodynamic evaluation for a small scale compressed air energy storage system by integrating renewable energy sources – proceeding conference ICRERA2015, Palermo, November 2015

8.MASON J.E., ARHER C.L., Renewable and Sustainable Energy Reviews, **16**, 2012, p. 1099

9.BAGDANAVICIUS A., JENKINS N., Energy Conversion and Management, **77**,2014, p. 432

10. KUSHNIR P., DAYAN A., ULLMANN A., International Journal of Heat and Mass Transfer, **55**, 2013, p. 5616

11.BULLOUGH C., GATZEN C., JAKIEL C., KOLLER M., NOWI A., ZUNFT S.,Advanced adiabatic compressed air energy storage for the integration of wind energy, in EWEC 2004, London, November 2004.

12. RAJU M., KHAITAN S.K., Applied Energy, **89**, 2012, p. 474

13. DRURY E., DENHOLM P., SIOSHANSI R., Energy, **36**, 2011, p. 4959

14. JUBEH N.M., NAJAR Y.S.H., Applied Thermal Engineering, **44**, 2012 p. 85

15. LUND H., SALGI G., Energy Conversion and Management, **50**, 2009, p. 1172

16. CROTOGINO F., Compressed air storage, in at EUROSOLAR, International Conference Energieautonomie durch Speicherung Erneuerbarer Energien, Gelsenkirchen, October 2006

17. LI Y., WANG X., LI D., DING Y., Applied Energy, **99**, 2012, p. 316

Manuscript received: 2.03.2017