TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 127, 2015, 7–25

JAN KICIŃSKI*

New ideas in distributed cogeneration and power engineering

The Szewalski Institute of Fluid Flow Machinery of the Polish Academy of Sciences, Fiszera 14, 80-231 Gdańsk, Poland

Abstract

This paper presents examples of technologies for distributed energy generation developed at the The Szewalski Institute of Fluid Flow Machinery of the Polish Academy of Sciences in Gdańsk. These are combined heat and power (CHP) units (generating heat and electricity) for houses with a power from several to tens of kW and for municipalities in the form of the Municipal Energy Centres (with a capacity of several hundred kW up to several MW). A unique project, specializing in 'energy-plus' technologies for individual houses and other buildings, which aims to build a Research Centre of PAS in Jabłonna is also presented. These are key technologies for energy sector with respect to distributed generation. Additionally, the article discusses the conditions and opportunities for the development of civil energy generation in our country. Civic energy generation is a great vision in which the citizen becomes an entity and do not subject to the energy market, and additionally has its virtual advisor in the form of smart grid and data processing technologies in a 'digital cloud'.

Keywords: Distributed generation; Renewable energy sources; Ecological power engineering

*E-mail address: kic@imp.gda.pl

1 New energy policy of the European Union related to the civil energy generation

Following the recent actions of the European Union, it can be concluded that the previously approved strategic direction of the EU policy aimed at reduction of emissions, introduction of renewable energy sources and energy conservation in buildings will not only continue, but also will be strengthened. Framework activities in this area are defined by **Energy Road Map 2050 (ERM2050)**, which is currently under preparation, new support mechanisms in the form of Framework Programme **Horizon 2020** (research and innovations) as well as by already functioning tools such as **SET Plan** (implementations, cooperation with industry), which are currently being improved and broadened. One thing is certain: the above-mentioned EU legislation clearly determine the path for the energy system development based on renewable energy sources, in particular small-scale and distributed.

In the light of the comments on these legislative initiatives, regardless of the pace of the works and the dangers arising from the lack of a stable law, one can expect a dynamic development of **intelligent and distributed energy systems** as well as significant improvement in energy efficiency. In this context, it is important to stimulate the development of activity of **prosumers** (producers who are simultaneously the consumers of energy), i.e., millions of small investors who are microscale producers of energy for their own use, selling the excess energy produced to the national power grid. This idea is a great opportunity for the traditional large-scale power engineering, because the possible lack of capacity can not be so quickly replaced by large conventional units (new power units) entailing considerable investments.

Additionally, this article discusses the conditions and opportunities for the development of prosumer energy generation or more broadly: civic energy generation in Poland and other countries. **Civic energy generation** is a great vision in which the citizen becomes an entity and not the subject of the energy market, and additionally has its virtual advisor in the form of smart grid and data processing technologies in a 'digital cloud'.

Studies on the conversion of energy from renewable sources require a multidisciplinary approach. Hence the need for a systematic synergy of scientific achievements in the field of technical, biological and agricultural sciences, but first of all in the field of ecological power engineering.

Summarizing the above considerations it can be concluded that the distributed energy engineering based on renewable energy sources (DES/RES), 'Smart Grid' and applications in the 'digital cloud' will be a key element of national energy policy in EU in the near future. This means that the hybrid systems integrating solar, biomass and wind technologies, heat pumps and energy storage for energy-plus residential houses, facilities and housing estates co-working in a smart grid are a challenge for the moment. In this context, the main task for national research centres, industry and self-government entities will be to develop economically viable solutions for the market using multivariate synergies between the different technologies and the elaboration of the most useful applications for the processing in 'digital cloud' [1–11].

The development of distributed energy generation system (DES) is directly related to the implementation of **intelligent energy management systems** (SG – Smart Grid). Smart grids will enable easier connection of distributed sources to the National Energy System, reduce the grid load and minimize the risk of blackout.

It is worth to emphasize that a smart grid itself in the electricity distribution system is only a certain technical layer. More important is that through the use of this grid, one can generate new services as well as new applications and as a result – simply make money. The grid itself is not able to trigger such changes but attractive applications are. It is worth noting that, for example Apple Inc. company succeeded predominantly thanks to applications rather than smart phones themselves.

In order to take advantage of all its benefits, the smart grid must be provided with appropriate **IT interface layer** enabling prosumers' communication in the so-called 'cloud computing' – Figs. 1, and 2. The term 'cloud computing' is here quite contractual. Although it is used in the literature in rather different contexts, its main features will find application in relation to the distributed eco-energy generation. There will be a place for different kinds of virtual installations, business models or even advisory systems applying artificial intelligence methods. The 'cloud', defined and understood as above mentioned, will be in fact **a virtual platform for the exchange of information for prosumers**, their data and knowledge bank as well as their system of professional advice. This is undoubtedly the future of this sector of energy engineering and a targeted vision of **civic energy generation**, where prosumers and consumers feel independent and free.

Similarly to the rapid development of ICT, which resulted in freedom of communication among citizens, one can expect that the development of distributed technologies (DES/RES) in combination with the smart grids and virtual communication platform for prosumers will make the citizens free also from the energy point of view. It's a great vision, which shall be given more attention – Fig. 1. Figure 3 shows the advantages of small-scale distributed cogeneration in comparison with a classic, large-scale power system.

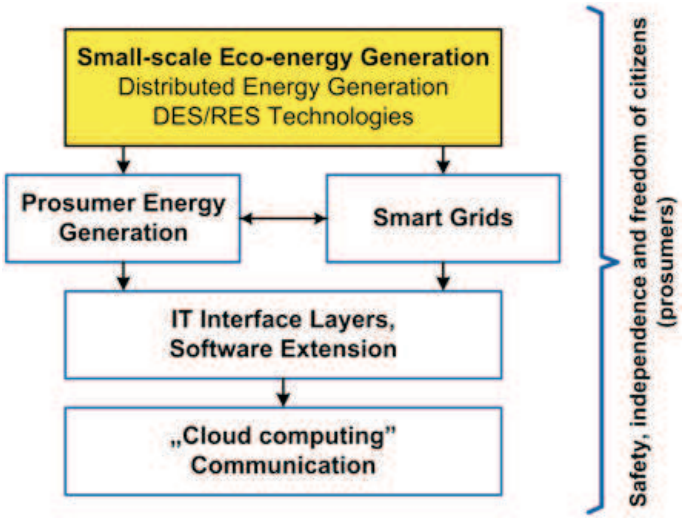

Figure 1: The development of small-scale eco-energy production as a vision of civic energy generation: from DES/RES technologies to processing in the 'cloud'. The vision of safety, independence and energy related freedom of the citizens.

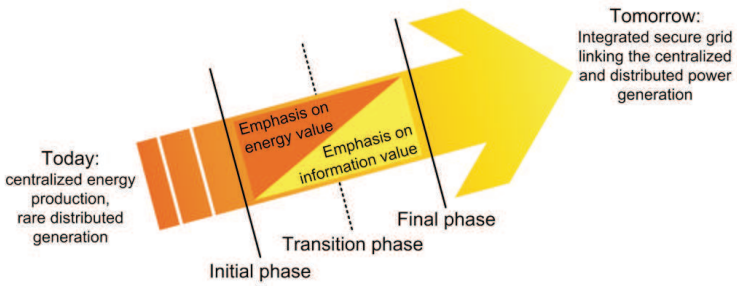

Figure 2: The role of information in the development of energy systems.

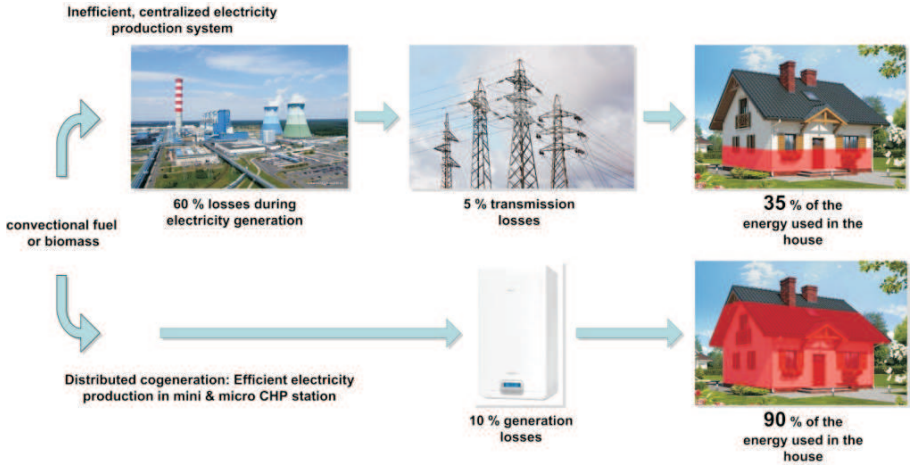

Figure 3: The advantages of distributed cogeneration in comparison with centralized power generation.

2 Installations for distributed energy. The examples of DES/RES devices and technologies

The following examples will refer only to the several selected research projects coordinated by the IMP PAN (Institute of Fluid-Flow Machinery of the Polish Academy of Sciences) in Gdańsk. However, these are the largest research projects in the country regarding the field of RES-based eco-energetics. They can therefore be treated as representative ones for this energy sector in one of the EU countries (Poland).

This article will focus on the results of the work related to so-called '**energy-plus**' technologies and **small & micro-combined heat and power units**. These results are the effect of research conducted at the institute and in cooperation with industrial partners (mainly the Capital Group ENERGA) and more than a dozen research teams from different research centres across the country. These study focuses on the future implementation and is addressed to individual and municipal consumers.

It is not the intention of the author of this article to present any other DES/RES technologies known in the country and especially in the EU even in the field of combined heat and power units.

When it comes to the ongoing studies, the construction of the CHP ORC plant is planned (the blocks consisting of a boiler and a microturbine

operating with a low-boiling agent using an organic Rankine cycle) with the electric power of several kW and tens of kW of thermal power. In the framework of the another project it is planned to build CHP ORC units of higher power (hundreds of kW of electrical power, thermal power up to several MW).

The results of these projects will be thus addressed to individual customers in the form of **domestic CHP units**, and to the municipal customer as **Municipal Energy Centers or Autonomous Energy Regions (ARE)**. Figure 4 shows this pictorially.

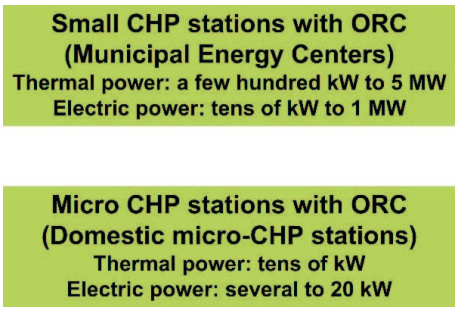

Figure 4: CHP ORC stations in small- & microscale as suggested in the framework of the IMP PAN projects.

3 Domestic CHP ORC units

One of the main purposes of the projects is to elaborate several prototypes of the so-called domestic CHP stations, which will include biomass and multifuel boilers with a capacity of tens of kW coupled with micro-turbine with a capacity of a few kW – operating with a low-boiling agent using an ORC (organic Rankine cycle). The concept of Domestic Cogeneration Units i.e., small plants that produce heat and electricity, may be attractive to thousands of individual customers, especially if the micro-CHP units will be integrated with other systems (solar/wind/water energy, heat pumps and energy storage), creating the so-called **hybrid systems** with greater mutual synergy – Fig. 5. Such micro-CHP units could create a new and powerful market and play a key role in the concept of civic and prosument energy generation.

The IMP PAN group (that means: IMP PAN, Lodz University of Technology, Gdańsk University of Technology, University Warmia and Mazury)

developed two concepts of microturbines with a capacity of 3 kW (axial-flow and radial-flow) coupled with multifuel boiler with a capacity of 20 kW (biomass or gas fired). As far as microturbines are concerned, the essential idea was to use the low-boiling agent (turbine's working medium) for bearing lubrication, which ensures tight and hermetic construction. Figure 6 shows this idea, while drawings and photographs of microturbines are presented in Figs. 7 and 8. Figure 9 shows the photo of test stand in the microturbine laboratory (located at the IMP PAN in Gdańsk) and the photo of multifuel boiler.

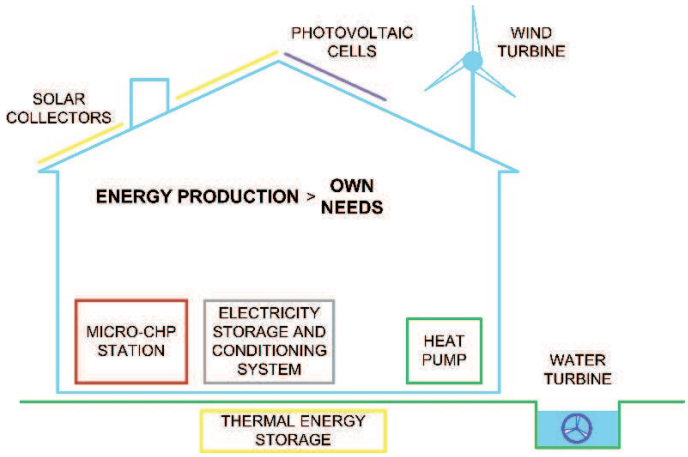

Figure 5: Domestic CHP units – an example of the hybrid system with a much greater mutual synergy. The attractive vision of civic or prosumer energy generation for thousands of individual customers.

Currently, laboratory investigations are carried out and as a result the boiler and both versions of microturbines are being tested. After completion of tests, the development of a target version (and perhaps commercial one) of an entire micro-CHP unit is planned. The brief foredesign and initial documentation of such micro-CHP station have already been elaborated – Fig. 10. If this undertakings are successful, it will be **the first in the country construction** of this type. Figure 11 shows the developed targeted versions of microturbines and Fig. 12 working version of wind turbine of low power (2–3 kW).

Important elements of the research are also energy storage devices. In the course of construction are modern stations with phase-change materials (PCM) that complement the concept of home power plant – Figs. 13 and 14.

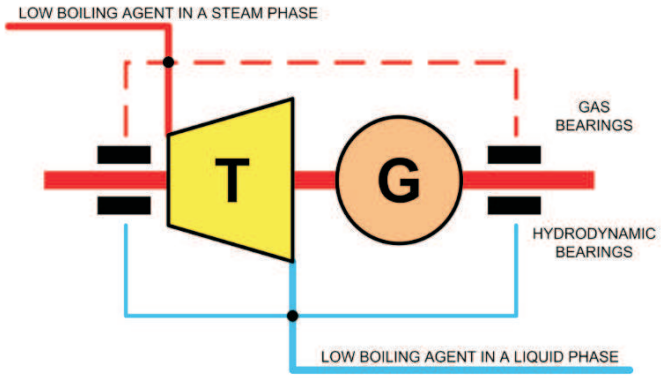

Figure 6: The possibility of utilization of a microturbine's working medium in the liquid and gas phases as a bearing lubricant. The concept of hermetic construction of a turbine, T, and a generator, G, to facilitate the integration with a boiler.

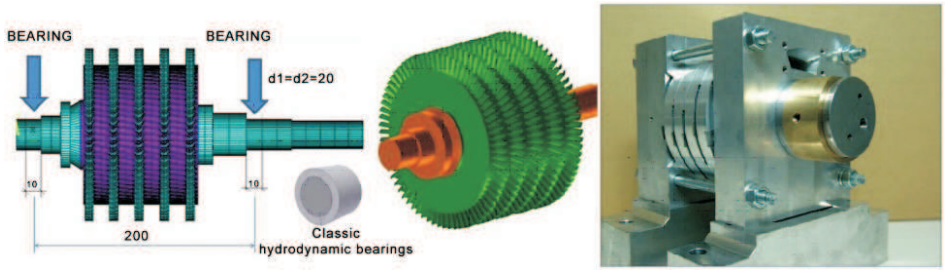

Figure 7: The first concepts: the axial-flow microturbine, 5 stages, with a capacity of 3 kW and rotational speed 8000 rpm. Tests are currently underway in the laboratory of the IMP PAN (developed by a research group of the Gdańsk University of Technology).

As part of the conducted projects, an attempt was made to develop a 'software upgrade' for the Smart Grid systems. These are the origins of an advisory system which cooperates with an individual user in the virtual space. The system, called **SoftRol** was developed by a group of the Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn – Fig 15. Currently the database (data on technology, type of crops, the size of an acreage) and also the knowledge base (simple business models) are being built along with testing of the entire system.

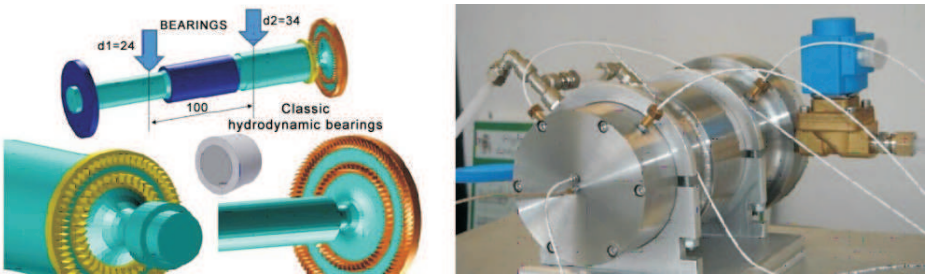

Figure 8: The first concepts: radial-flow micro-turbine, 4 stages, with a capacity of 3 kW and rotational speed 23 000 rpm. Tests are underway in the laboratory of the IMP PAN in Gdańsk (developed by a research group of the Lodz University of Technology).

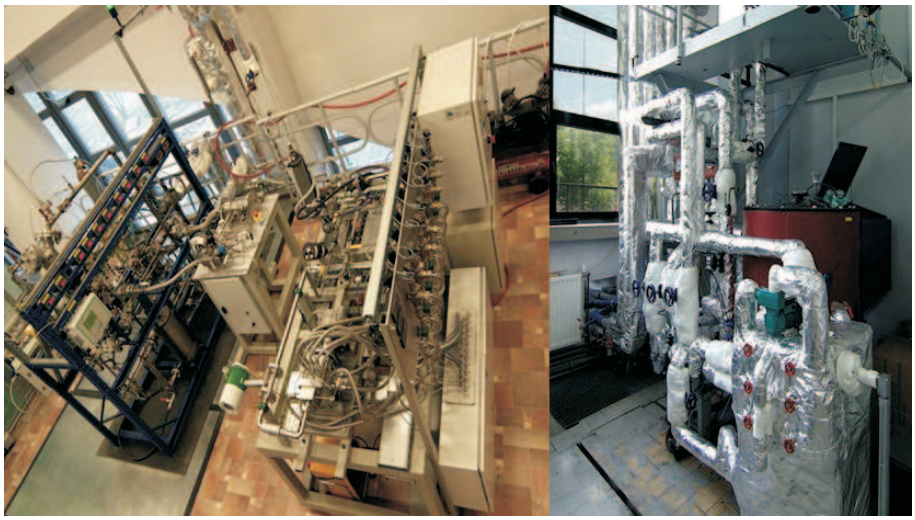

Figure 9: The laboratory of the IMP PAN in Gdańsk: Pictures of microturbine test stand (on the left) and multifuel boiler (on the right).

4 Autonomous Energy Regions (ARE)

Concept, assumptions for and building of the Autonomous Energy Regions (ARE) or Municipal Energy Centres is one of the main tasks of the conducted projects. Construction of the ARE is an excellent example of cooperation between science and industry on such a large scale, in this case, between the IMP PAN and ENERGA Group. In cooperation IMP PAN – Energa the modern installations are built dedicated to distributed genera-

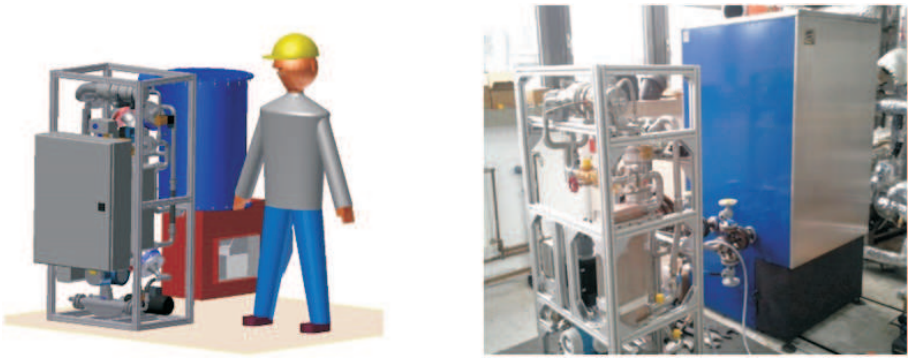

Figure 10: Target design of Domestic Micro-CHP Unit with ORC after all examinations and tests in the laboratory of the IMP PAN in Gdansk. The first concepts (left),: commercial version of the installation (right).

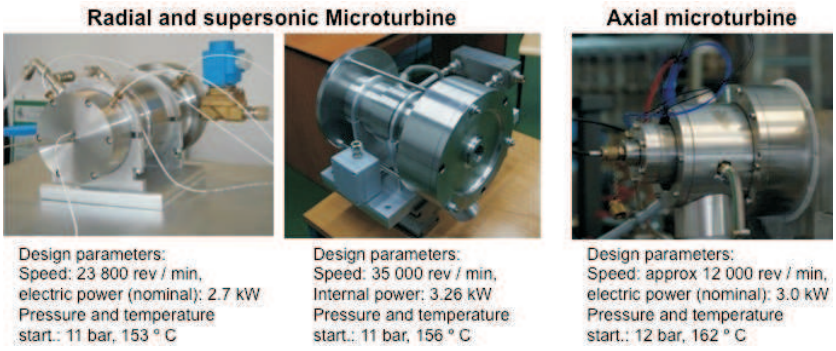

Figure 11: Domestic Micro-CHP-ORC Unit. Microturbines developed target versions, elaborated in Lodz UT and Gdańsk UT in cooperation with IMP PAN.

tion, which are demonstratively shown in Fig. 16.

The significant feature of this cooperation is the number of innovative, prototype installations that are to be built upon its completion in 2015. Over a dozen of these installations will be created, with two flagship ones (ARE) in selected municipalities in Poland. For obvious reasons we will not discuss these systems in this paper. ARE will play a key role (along with Domestic CHP Units) in the concept of distributed and civic energy generation.

The Autonomous Energy Regions (ARE), equipped with new technologies and CHP systems, become the **project** that creates a great opportunity for economic development of the Polish countryside. ARE is a concept that should direct Poland into the path of changes that are already occurring

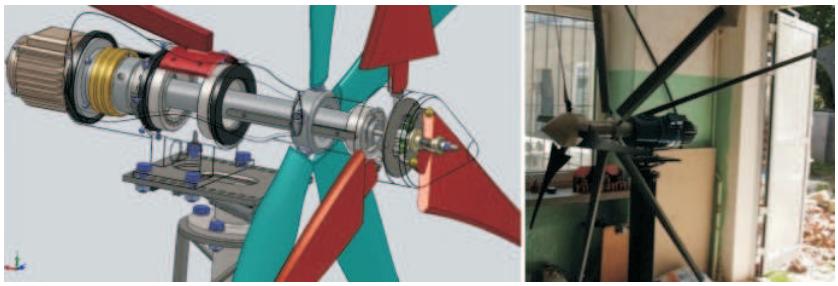

Figure 12: Two-rotors wind turbine with a horizontal axis. The proposed design solution enables the use of high-speed wind turbine power generator without the use of multipliers. Elaborated in University of Warmia and Mazury in Olsztyn.

Figure 13: PCM-based energy storage prototype in the lab in the IMP PAN (testing rig is currently under construction).

around the world. Currently, in Europe and in North America, as well as, in China 'green' villages, housing estates, districts and even cities are being developed (where 'green' means emission-free, zero-energy or energy-plus).

The installation which is currently being built in one of the communities in Poland will serve as a **role model of a small-scale CHP plant**. In place of the old-fashioned heat-generating plants, modern cogeneration units will be built, which include – Fig. 17:

- ORC system with an electric capacity of 0.143 MWe and the heating capacity of 0.83 MWt,
- CHP system with two combustion engines powered by natural gas

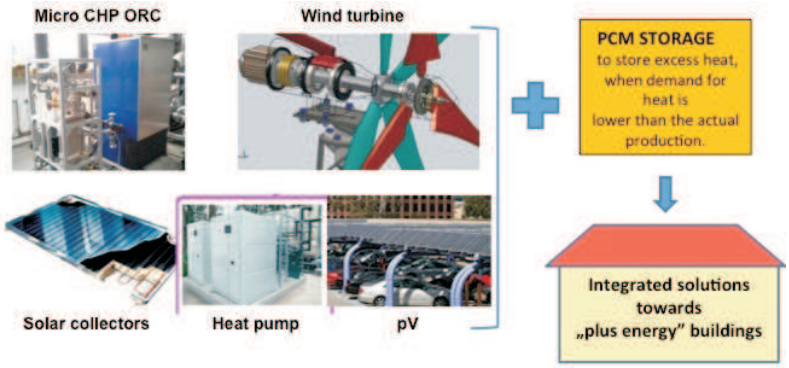

Figure 14: Energy storage – a key factor in plus-energy buildings.

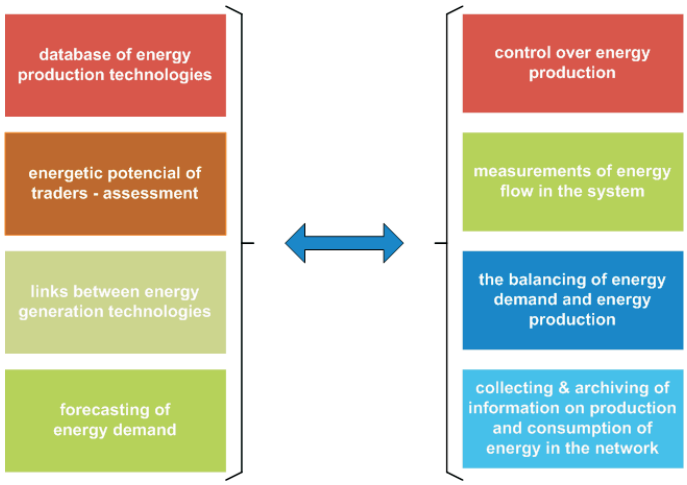

Figure 15: SoftRol system as an example of data and knowledge base ('software upgrade' for the Smart Grid systems). SoftRol functions (on the left), Smart Grid functions (on the right). Developed by a group from the Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn. The system currently undergoes a test phase.

with a total electric capacity of 3.1 MWe and the heat capacity of 3.4 MWt,

- biomass-fired steam block with the electric capacity of 2.7 MWe and heating capacity of 5.2 MWt,
- supplemented with an upgraded exhaust gas extraction system and backup boilers.

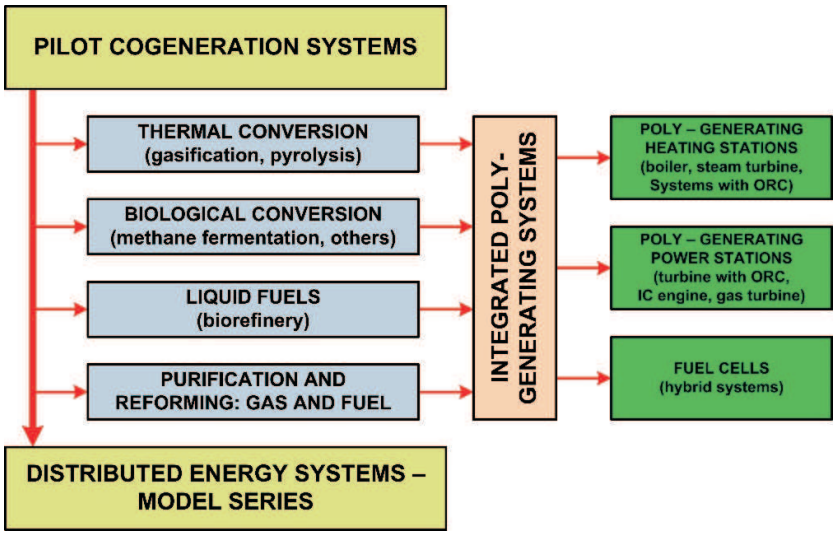

Figure 16: Installations built in the framework of the IMP PAN and Energa Group dedicated to the ARE and distributed generation.

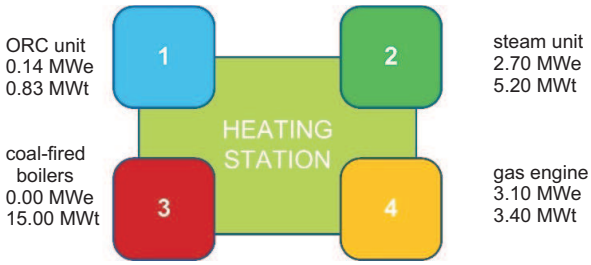

Figure 17: The first ARE in Poland – the clue of the concept of modernization of the heating station in selected municipalities: several flexible CHP modules, including the module with ORC operating all year round.

The solution shown in Fig. 17 exhibits the unquestionable technological progress in the field of energy solutions in the Polish municipalities.

What is the essence of the proposed first ARE in Poland? The biomass CHP system with ORC – designed to cover the summer demand for domestic hot water – will be working continuously throughout the whole year, while other systems will be started in response to the heat demand (this limitation is particularly important for combustion engines, for which the income from electricity production does not cover operating costs and is balanced by the income from heat generation). The steam block is planned to be operated all

year round. During the heating season it will work in a heating mode (with steam bleeding), and then in condensing mode with maximum efficiency in electricity production. When the heat demand increases then reserve, coal-fired boilers will be switched on.The above idea solves an extremely difficult problem of this type of heating stations in the country, i.e., what to do with excess heat during summer? It is estimated that in Poland there exist over 300 heating stations of a similar, old-fashioned type! If the idea is successful (and success is highly probable due to the scale of involvement of a large industrial partner), suggested solutions can be copied across the country in municipalities and housing estates.

Laboratory of the microsteam power plants is currently constructed in the IMP PAN in Gdańsk – Figs. 18 and 19. This modern and largest laboratory in the country is financed from the EU funds. In the future, this laboratory will also serve as a back-up research facility for devices and technologies to be applied in ARE.

Figure 18: The largest in Poland micro-CHP Laboratory: the poligeneration power plant in the IMP PAN in Gdańsk.

5 Research Centre in Jabłonna

Trends related to the development of distributed energy generation were the basis of decision made by the Polish Academy of Sciences and the Office of the Marshal of Mazowieckie Voivodship to build, a new and unique in the country, Research Centre – Figs. 20–22. This Centre will be dedicated to the investigation of aspects of renewable energy conversion. The Centre, (to be located in the municipality of Jabłonna, about 20 km from Warsaw), is planned to serve as a complex of modern research/testing laboratories

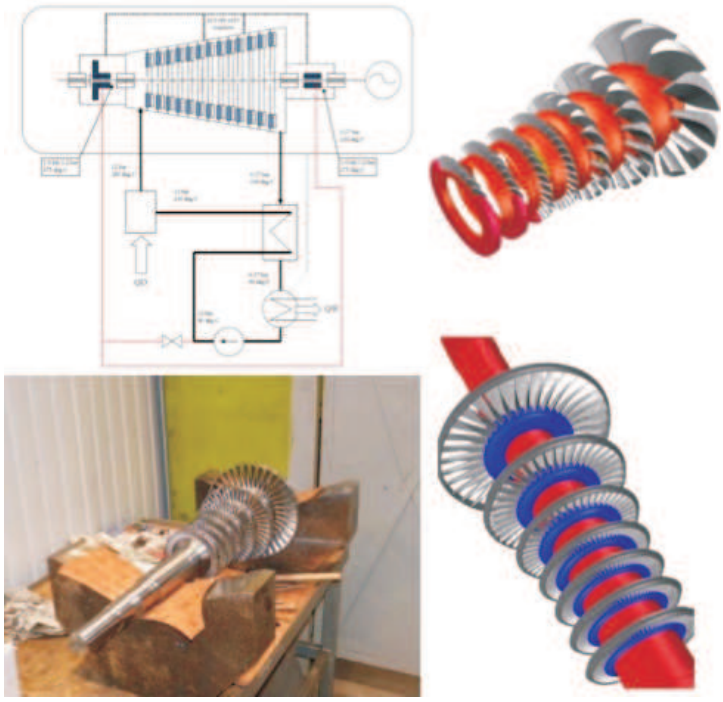

Figure 19: IMP PAN Laboratory: ORC turbogenerator (own solutions) for ARE; axial turbine 9000 rev/min, 100 kW.

with a unique apparatus and a set of demonstration facilities concerning distributed energy systems (DES), as well as, technologies for the so-called energy-plus houses and facilities – Fig. 22. The beneficiary is the IMP PAN in Gdańsk, who developed the concept of the Centre and coordinates its implementation. The completion of the investment is scheduled for December 2014 but activities related to design and legislative work, planning of research and consolidation of scientific and industrial centres have been ongoing since 2012.

The Centre will be equipped with a local intelligent 'Smart Grid' system which makes it possible not only to manage energy sources and the way energy is stored, but also remote archiving, transmission and processing of the experimental data obtained from research laboratories. The set of conference rooms, guest rooms, recreational areas and RES Education Path will enable Centre to fulfil also the important educational and training functions.

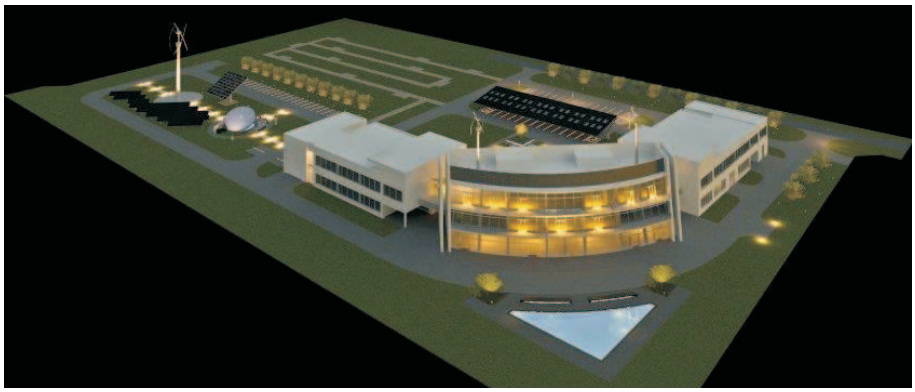

Figure 20: The new 'Energy-plus' Research Centre of the Polish Academy of Sciences in Jabłonna. Energy-Plus technology for small private and public buildings.

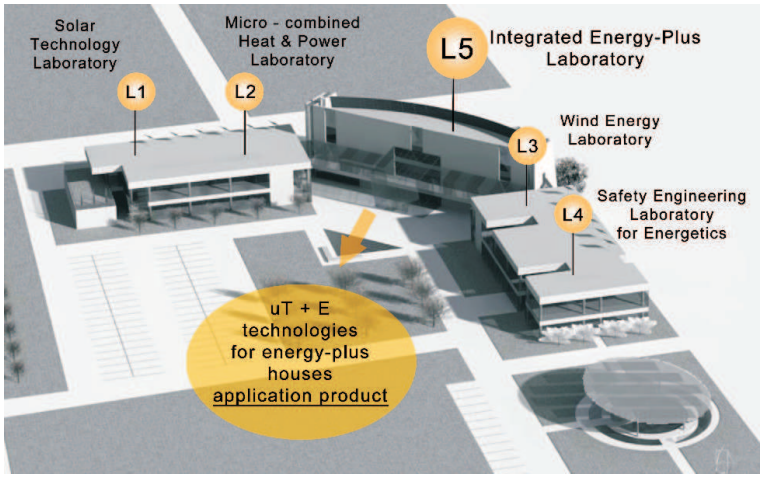

Figure 21: The view of the Research Centre in Jabłonna from the north – location of laboratories.

The energy systems installed at the Centre – in the power range from a few to several hundred kW (biomass and gas boilers, combustion engines, gas and wind turbines, heat pumps, solar collectors, photovoltaic (PV) cells and several types of energy storage), thanks to the possibility to create multiple variants and operational modules as well as the original hybrid associations, offer unique research opportunities for testing and certification of these devices. This is particularly important given the fact that all these devices are concentrated in one place and operate within a single system of

Figure 22: The Research Centre's offer for local scientific community, self-government and industrial entities. 'Business card of the centre' – Energy-Plus Technologies for houses, facilities and housing estates (uT+E).

energy/information management (expanded BMS). The achievement of the so-called 'synergy effect' in these conditions is certainly facilitated.

6 Concluding remarks

This article presents only a few selected examples of specific devices (DES/RES) developed within research projects conducted by IMP PAN in Gdańsk. These are:

- Domestic CHP Units,
- CHP Plant in selected municipalities as an example of a ARE (Autonomous Energy Regions),
- Research Centre in Jabłonna – Energy-Plus Technologies for houses, facilities and housing estates (uT+E).

All of the above installations and laboratories might play an important role in the development of small-scale distributed power generation in Poland and in EU countries.

The question whether these devices and the offer of Research Centre in Jabłonna will become an important element of the concept of **prosumer**

energy generation or (more broadly) **civic energy generation** depends on many factors, the most important are:

- stable legislation supporting concepts and installations of this type,
- stable and favourable legislation for consumers and companies,
- sufficient development of intelligent 'Smart Grid' system,
- development of cost-effective DES/RES technologies.

The above issues are part of the energy and economic policies of individual countries. The author of this work hopes, that appropriate legislative action will be taken in the near future.

Received 20 February, 2015

References

[1] Kiciński J.: *Do we have a chance for small-scale energy generation? The examples of technologies and devices for distributed energy systems in micro and small scale in Poland*. B. Pol. Acad. Sci-Tech, **61**(2013), 4, 749–756.

[2] Yanine F.F., Sauma E.E.: *Review of grid-tie micro-generation systems without energy storage: Towards a new approach to sustainable hybrid energy systems linked to energy efficiency*. Renew. Sust. Energy Rev. **26**(2013), 60–5.

[3] Kaygusuz A., Keles C., Alagoz B.B., Karabiber A.: *Renewable energy integration to smart cities*. Energ. Buildings **64**(2013), 456–462.

[4] Markovic D.S., Zivkovic D., Branovic I., Popovic R., Cvetkovic D.: *Smart power grid and cloud computing*. Renew. Sust. Energy Rev. **24**(2013), 566–577.

[5] Sliz-Szkliniarz A.: *Assessment of renewable energy-mix and land use trade-off at regional level: A case study for the Kujawsko-Pomorskie Voivodship*. Land Use Policy **35**(2013), 257–270.

[6] Scleicher-Tappeser: *How renewables will change electricity market in next five years*. Energy Policy **48**(2013), 64–75.

[7] Kiciński J., Żywica G.: *Numerical analysis of defects in the rotor supporting structure*. Adv. Vib. Eng. **11**(2012), 4, 297–304.

[8] Kiciński J., Żywica G.: *The numerical analysis of the steam microturbine rotor supported on foil bearings*. Adv. Vib. Eng. **11**(2012), 2, 113–120.

[9] Kiciński J.: *Computational model and strength analysis of the steam microturbine with fluid-film bearings*. Proc. of Int. Conf. on Vibration Engineering and Technology of Machinery VETOMAC-VIII, Gdańsk, 3-6 Sept., 2012, VM 2012-10005, 333–342.

[10] Kiciński J.: *New method of state analysis and diagnostics of power micro-devices*. Sci. Probl. Machines Oper. Maint. **46**(2011), 1 (165), 57–69.

[11] Kiciński J., Żywica G.: *Steam Microturbines in Distributed Cogeneration*, Springer 2014.