Title:	**Flexible Multi-Generation Solutions for Future Low Carbon Energy Systems**
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Although today's energy systems are in fact multi-energy system, it is very arguable how much flexibility and efficiency from coupling different energy vectors (electricity, gas, heat, cooling etc) through known technologies is presently exploited. Energy strategies are implying that changes in traditional systems planning and operation are inevitable and will be dictated by the increasing share of intermittent renewable energy sources, such as wind and solar, together with goals of decarbonising the entire energy sectors. Investment planning decisions in energy business go beyond 30 year planning period and it is obvious that the fossil fuels will have an impact in the future low carbon energy systems. This underlines an important strategic, operational, environmental and investment issue: which solutions are capable of complying with these demands and, at the same time, cope with the increasing flexibility requirements of future power systems. These increasing flexibility requirements are caused by volatile electricity generation in power systems with high penetration of renewable energy sources. The price of having high percentage of renewable generation in the system is being able to balance them with flexible, usually carbon intensive, generation. This issue brings up an important question: will large share of renewable sources bring us closer to a goal of low carbon systems if we need environmentally unfriendly generations to balance their variability? Is this the best solution?

Electricity sector decarbonising strategies are being followed by similar actions in heating, displacing carbon emissions usually by electrifying heat (the UK strategy suggests that 30 million new domestic electric heat pumps will be installed by 2030). The question is will the future heat sector, based on electric heat pumps and/or electric resistors bring further value to the increasing demand for flexible electricity systems. Distributed Generation (DG) has been seen by many as the electricity production paradigm of the new millennium. In recent years, the Distributed Multi-Generation (DMG) concept has emerged beyond electricity, whereby DG technologies based on thermal prime movers are capable of increasing the overall generation efficiency by producing manifold forms of energy, such as electricity, heat, cooling, and so forth. Knowing this we have asked ourselves: is coupling these vectors through combined heat and power generation a better strategy than relaying solely on electrifying heat? Or is the optimal solution the combination of benefits that can be extracted from both these options?

The aim of the research at the University of Manchester was to develop a techno-economic operational optimization model for DMG plants which takes into account the interaction with the upstream energy systems and markets, specifically taking into account the flexibility that can be made available by aggregating and managing multi-energy generators, loads and storage. In fact, depending on the specific multi-energy load configuration and energy price conditions for different energy vectors (for instance, natural gas, electricity, and heat), by energy shifting from one form of energy to another or by decoupling generation and demand through thermal storage, DMG plants are capable to efficiently react to external signals. In addition, by deploying this multi-energy flexibility, DMG systems have the potential to provide power system multiple services such as frequency regulation, different forms of reserves, and network capacity support. Hence, besides increasing generation efficiency, DMG plants also represent an interesting option to support the demand-supply balancing task in future power systems with increasing intermittent generation (mainly wind) and inflexible conventional generation such as nuclear and carbon capture and storage.

Despite many open issues there are very few models capable of explaining benefits which can be derived from each of different Multi-Generation options. The work carried out at the University of Manchester was aimed at creating an original, unified and comprehensive Mixed Integer Linear Programming (MILP) model suitable for evaluating incremental economic flexibility and environmental benefits from different Distributed Multi-Generation (DMG) options. The developed model demonstrates different options operational cost benefit and flexibility to respond to electricity market signals. It recognizes that the value of flexibility can be gained thru shifting between different energy vectors, without affecting the quality of service for the end consumer. We have performed detailed sensitivity analyses of different DMG configurations, and have exemplified them through realistic case studies, clearly showing how much flexibility and what economic and environmental benefits can be derived from coupling different energy vectors and by cascading cogeneration units and electric heat pumps supported with thermal storage.
It is very important to notice that the entire research is led by several important guidelines:

- The original model and all the analyses are based only on the existing technologies, only those available on the market (and economically feasible) are taken into the consideration. However, the model is quite modular and can easily be expanded to incorporate future available technologies such as electric vehicles, smart homes, battery storage etc.
- The entire concept that has been developed lays on the assumption that the consumer does not have to actively participate in changing his behaviour to help the energy system. Although many researchers claim future system will require the consumers intelligent interactions with the energy devices we made the assumption that this is not required.
  To elaborate we can draw a parallel with the ICT industry: would you be using your Smartphone or a tablet if it required that you understand and know how to program in order to use it? Our answer is - NO. For this reason we consider energy consumers as costumers requiring a level of comfort and service. The financial and environmental benefit is extracted only by intelligent control algorithm we have developed.

Besides creating an original mathematical model we have conducted multiple analyses of the unit and system benefits for the newly proposed paradigm. As a result of these analyses we made several important conclusions:

- DMG units based on coupling different units such as internal combustion engine, electric heat pumps and thermal storage can **reduce the operational cost by over 50%** compared to the traditional systems we currently have!
- These units bring significant CO_2 savings, having **carbon emission reduced by over 40%** compared to the present situation and presently used systems.
- The cost benefit analyses have shown these units have a high Net Present Value and are less sensitive to discount rates than presently used concepts. Even with high discount rates we have shown an investment return in the period shorter than 6 years.
- Local emissions are very rarely conducted in energy analyses, but they are the ones affecting the population the most. As DMG units are installed closer to the population we believe that local emissions are a crucial factor when deciding on installing these smaller units instead of larger ones, further from the population. **We have shown that the emissions of CO and NO_x do not increase when compared to traditional electricity and heat systems despite the proximity of generation units**.
- It should be kept in mind we conducted all the analyses for natural gas based systems.

Having this in mind, and considering that proposed concepts are applicable to biogas or biomass systems, **all the environmental benefits are in fact a conservative assessment, despite the high CO_2 emissions savings**.

As a result of the research conducted at the University of Manchester we have submitted several papers:

Conferences:

- Tomislav Capuder, Pierluigi Mancarella, Davor Skrlec: "*Flexible District Heating Multi-Generation Options*", IEEE Power and Energy Society General Meeting, Vancouver, Canada, July 2013
- Tomislav Capuder, Pierluigi Mancarella, Davor Skrlec: "*Market Driven operation of Flexible Multi-Generation Units*", 8th Conference of Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, September 2013.

Journals (Current Content indexed):

- Tomislav Capuder, Pierluigi Mancarella, Davor Skrlec: "*Environmental Impact of Large Scale System Integration of Microgrids*", submitted to IEEE Transactions on Sustainable Energy
- Tomislav Capuder, Pierluigi Mancarella: "*Techno-economic and Environmental Modelling and Optimization of Distributed Multi-Generation District Heating Options*", submitted to Energy

The research on the topic is ongoing and we are planning on writing and publishing several other papers (2 journal papers in addition to the ones mentioned). The worked carried out in UK and after the visit resulted is a significant contribution to my doctorate research. As a result I plan on submitting my PhD thesis by the end of 2013.
Dr. Pierluigi Mancarella has also offered me a post doctorate position at the University of Manchester to lead the group of PhD students working on a project of future energy networks.