# $CO_2$ Emission Reduction from Sustainable Energy Systems: Benefits and Limits of Distributed Multi-Generation

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***Abstract* — The struggle to decarbonise future power systems is boosting the diffusion of high-efficiency distributed multi-generation (DMG) systems. In this respect, small-scale (below 5 $MW_e$) cogeneration systems for producing heat and power, as well as trigeneration systems for additional production of cooling, could play a key role. In this paper, a general analytical model for assessing the potential $CO_2$ emission reduction from DMG systems, in case coupled to heat/cooling networks, is presented. Different available solutions are analysed. Numerical applications make reference to typical emission intensity figures in Europe. The results show that the emission reduction potential is primarily a function of the electrical efficiency and therefore of the size, and is strongly affected by the baseline comparative references. The environmental benefits decrease if part of cogenerated heat is used to generate cooling power with single-effect absorption chillers or adsorption chillers.**

***Keywords - cogeneration, distributed generation, emission reduction, heat networks, trigeneration.***

## NOMENCLATURE

| | |
|---|---|
| CHP | Combined Heat and Power |
| CCHP | Combined Cooling Heat and Power |
| DHN | District Heating Network |
| DMG | Distributed Multi-Generation |
| ICE | Internal Combustion Engine |
| MT | Microturbine |
| SE | Stirling Engine |
| SP | Separate Production |
| *TCO2ER* | Trigeneration $CO_2$ Emission Reduction |
| WAC | Water Absoprtion/Adsorption Chiller |

## I. INTRODUCTION

The evolution of power systems is being deeply influenced by the growing need for cutting $CO_2$ emissions from energy generation. Combined Heat and Power (CHP) plants allow more efficient fuel energy input utilization with respect to classical Separate Production (SP) means in which electricity is generated in centralized power plants and heat in traditional boilers [1]. This enhanced overall efficiency can bring along $CO_2$ emission reduction, also depending on the fuel carbon content and on the emission intensity of the displaced sources. In the past, economy-of-scale factors limited the adoption of CHP plants to relatively large industrial users or District Heating Networks (DHN). Conversely, today various Distributed Generation (DG) technologies, potentially clustered within micro-grids [2] and mostly fuelled on natural gas, are available for local exploitation of cogenerated heat at different capacities. In particular, on a small-scale level (up to 5 $MW_e$) mature CHP prime movers include Stirling Engines (SE, available for micro-CHP applications in single dwellings, typically up to 10 $kW_e$) [3][4], Microturbines (MT, in the capacity range 30-300 $kW_e$), and Internal Combustion Engines (ICE, up to 5 $MW_e$) [4]. Heat networks may be needed to interconnect a set of possible users to a large prime mover, so as to establish an adequate overall thermal load.

As a further issue to be addressed, the profitability of CHP systems can be consistently affected by low thermal loads in the summertime, when the need for space heating is not present and only domestic hot water makes up the thermal demand. Hence, the CHP unit, sized on the basis of the winter thermal demand, could operate at partial load and often be switched off below a certain loading threshold, losing all or at least part of the benefits from cogeneration production. A spreading solution relies on the possibility of exploiting cogenerated heat for cooling production by means of Water Absorption or Adsorption Chillers (WAC) [5], leading to set up the so-called trigeneration or Combined Cooling Heat and Power (CCHP) plants [6]. Hence, in a CCHP plant, the CHP prime mover can be operated at high loading level also in the summertime, contributing to cover an air conditioning demand that is steadily rising even in the northern European countries. For larger plants, the DHN may be used for heat distribution and the WAC sited at the building user interfaces [5]. Smaller plants without heat networks adopt a centralized cooling plant sited close to the CHP system and to the user. Single or aggregated user typologies such as hotels, hospitals, restaurants, department stores, offices, banks, residential blocks are typical potential applications for trigeneration systems on various scales.

A CCHP plant is a particular case of the more general category of distributed multi-generation (DMG) systems [7] [8] enabling the dispatch of different types of energy and the conversion from one type of energy to another through suitably sized components, with possible other external networks for further exploitation of the energy products.

The authors have illustrated and discussed the DMG concepts and applications in recent references, following a research line developed to highlight the perspectives and assess the potential of DMG applications in terms of energy efficiency improvement [9]-[12] and environmental impact reduction [13]-[16], up to the formulation of a unified approach to define structured indicators to quantify the technical and environmental performance of multi-generation systems [17].

The cost effectiveness of distributed CCHP systems, above all if coupled to DHN, requires thorough assessment. However, before running detailed economic analyses, simple and synthetic environmental models are needed to assess in which conditions and to which extent combined generation of multiple energy vectors can bring $CO_2$ emission reduction relative to the *status quo*. In this respect, in this paper the *Trigeneration $CO_2$ Emission Reduction* (*TCO2ER*) indicator [18][19] is adopted to estimate the potential $CO_2$ emission saving characteristics from small-scale distributed trigeneration systems in different frameworks. The main objective is to formulate a simple analytical model, capable to highlight the parameters and variables involved in the analysis. The dependence of the emission reduction on the CCHP equipment efficiencies and on the emission intensities taken as reference for the conventional SP is investigated. Numerical applications are based on equipment currently available on the market and on the energy generation environment in Europe, with particular reference to the UK.

## II. TRIGENERATION SYSTEM STRUCTURE AND PERFORMANCE INDICATORS

### A. Structure, Components and Characteristics

A CCHP plant is composed of the combination of a CHP plant (with auxiliary boilers for thermal back-up and peak shaving, as well as, in case, thermal storage), and a cooling plant fed by cogenerated heat, with possible heat networks. The CCHP plant is further interconnected with the electrical distribution grid, to enable buying/selling electricity according to the rules for electricity provision (depending on the tariff system or electricity market structure).

Focusing on small-scale applications, we consider different types of technology, that is, SE, MT and ICE, all fed on natural gas. The WAC-based cooling plant can be composed of different technologies [6], to be suitably coupled to the CHP side. Single-effect absorption chillers, typically fired by hot water at around 90 °C, are considered in this paper for coupling to MT and ICE. Adsorption chillers, instead, may be fired by lower temperature sources and are available at capacities smaller than absorption chillers [5]; thus, they are adequate for combination with dwelling-sized SE. The CCHP system is usually electrically connected to the distribution network or to a microgrid.

### B. Energy Performance Models for Trigeneration Equipment and Heat Networks

The energy performance of CHP prime movers can be synthetically described by means of the electrical efficiency $\eta_W$ and the thermal efficiency $\eta_Q$. In addition, it is possible to characterize the CHP energy production in terms of heat-to-electricity cogeneration ratio $\lambda_y$ [1]:

$$\eta_W = \frac{W_y}{F_y}, \quad \eta_Q = \frac{Q_y}{F_y}, \quad \lambda_y = \frac{Q_y}{W_y} = \frac{\eta_Q}{\eta_W} \tag{1}$$

The terms *W*, *Q* and *F* in (1) respectively denote electricity, heat and fuel thermal energy, while the subscript *y* points out cogeneration entries.

As for cooling generation equipment, the energy characteristics of a WAC are described by means of the *COP* (Coefficient Of Performance), ratio of the desired output (cooling energy *R*, in the form of chilled water for instance at 7 °C) to the input (heat $Q_R$ in the form of cogenerated hot water) [5]:

$$COP = R/Q_R \tag{2}$$

All the above efficiencies depend upon the technology and upon several variables such as the loading level, the outdoor conditions, and so forth [4][5][20].

As far as heat networks are concerned, two types of losses are in general present, namely, heat losses $Q_L$ due to heat transfer with the colder external environment, and parasitic electrical pumping losses $W_L$ to overtake the hydraulic friction in the pipes. These loss contributions can be for instance expressed with respect to the cogenerated heat, as

$$\varepsilon_Q = Q_L/Q_y, \quad \varepsilon_W = W_L/Q_y = W_L/\lambda_y W_y \tag{3}$$

Typical values of percentage heat losses $\varepsilon_Q$ range between 1% for small networks (few hundreds meters) to 10%-15% for large DHN (tens of kilometers). Typical percentage electrical parasitic losses $\varepsilon_W$ due to pumping are of the order of 1% or even less for various applications [1][5].

### C. $CO_2$ Emission Performance Models for Trigeneration Equipment

A consistent approach to evaluate the environmental performance of a trigeneration system by resorting to a system-orientated black-box representation is based on taking into account the mass of carbon dioxide involved in the exploitation of the energy system.

The mass $m_X$ of $CO_2$ emitted to produce the *useful* energy output *X* can be worked out as $m_X = \mu_X \cdot X$, where $\mu_X$ is the $CO_2$ emission factor (specific emissions) related to the generic useful energy output *X* (e.g., electricity or heat). With very good approximation, it is possible to consider the emission factor $\mu_F$ related to the fuel thermal energy as a constant depending only upon the fuel carbon content and its Lower Heating Value (LHV). Hence, once given the fuel, the energy output-related emissions can be evaluated as a function of the device efficiency only, as [18][19]:

$$\mu_X = \mu_F/\eta_X \tag{4}$$

where $\eta_X$ is the equivalent efficiency to produce the relevant energy output *X* from the fuel energy input *F*, as for instance in (1) for CHP units. For natural gas, $\mu_F$ can be averagely assumed equal to 200 g/kWh$_t$, on a LHV basis [21].

## III. ENVIRONMENTAL ASSESSMENT MODEL

### *A. General Trigeneration CO$_2$ Emission Reduction Assessment Model*

In order to compare different energy generation alternatives, it is convenient to establish a reference scenario and to assess the various alternatives against this reference. For trigeneration systems, this can be carried out by introducing the *TCO2ER* indicator [18][19], expressing the relative reduction of the mass of carbon dioxide due to the use of a trigeneration system to displace the energy production needed to serve a certain energy output in the combined production of multiple energy vectors. From the conceptual framework used in cogeneration system analysis, the SP of electricity and heat comes from classical and standardized references (power generation system and boilers). It is however less immediate to identify the reference technology for SP of cooling. The authors in [9] introduced the assumption that the baseline technology reference for cooling power generation is an electric chiller, in turn supplied by the electrical network. Under this assumption, the *TCO2ER* indicator is expressed as

$$TCO2ER = \frac{m_F^{SP} - m_F}{m_F^{SP}} =$$

$$= 1 - \frac{\mu_F \cdot F_z}{\mu_W^{SP} \cdot \left(W_z + R_z / COP^{SP}\right) + \mu_Q^{SP} \cdot Q_z} \qquad (5)$$

The expression (5) applies to a general trigeneration plant with $F_z$ as the energy fuel input and electricity $W_z$, heat $Q_z$, and cooling energy $R_z$ as the threefold useful energy output. The subscript $z$ points out net input-output entries for the overall plant. Setting $R_z$ = 0 in (5) leads to cogeneration assessment as a sub-case. In terms of emission mass, $m_F^{SP}$ is the CO$_2$ mass emitted by combustion of the fuel thermal input $F^{SP}$ in order to produce the same amount of trigenerated energy in SP, while $m_F$ is the CO$_2$ mass emitted by combustion of the CCHP fuel thermal input. The model (5) can also be extended to entail the presence of distribution networks; in this case, the output entries are considered net of the distribution and parasitic losses. In terms of baseline references, the specific emissions $\mu_W^{SP}$ and $\mu_Q^{SP}$ represent the equivalent emission factors for SP, while $\mu_F$ refers to the CCHP fuel thermal input. Emissions from cooling generation are assessed through the reference electricity emissions, and considering an electric chiller with cooling-to-electricity efficiency equal to $COP^{SP}$. The emission factors and the chiller efficiency for SP are evaluated as conventional values. As such, they may be related to the underlying assumptions of the study, as illustrated in Section IV.

Positive *TCO2ER* values represent the existing convenience of adopting trigeneration to displace conventional energy generation in the supply of the corresponding energy demands. The maximum positive value of *TCO2ER* is unity (or 100%), ideally representing the adoption of a trigeneration system supplied by carbon dioxide-free fuel. Negative *TCO2ER* values (not limited in amplitude) indicate that introducing trigeneration to displace SP is not convenient.

### *B. Specific Energy System Model for CHP-WAC Trigeneration and Heat Network*

A more specific formulation of the expression (5) is derived here for the CHP-DHN-WAC energy system under analysis. In this respect, let us consider the plant model in Figure 1, in which all the equipment and the relevant efficiencies are schematized as black-boxes. All the energy produced is assumed to be utilized. More specifically, the cogenerated electricity $W_y$ coincides, net of the pumping losses for heat distribution, with the overall trigenerated electricity $W_z$, and goes to supply the local user or is injected into a local microgrid or the distribution network. The cogenerated heat $Q_y$, net of heat distribution losses, splits into two components, namely, $Q_z$ corresponding to the net trigenerated heat output for direct thermal purposes (for instance, domestic hot water generation and space heating), and the other one to fire a WAC for generating the trigenerated cooling energy $R_z$. The "splitting variable" is indicated as $\alpha_R$, and corresponds to the relative amount of cogenerated heat going to feed the WAC.

With reference to Figure 1, taking into account the

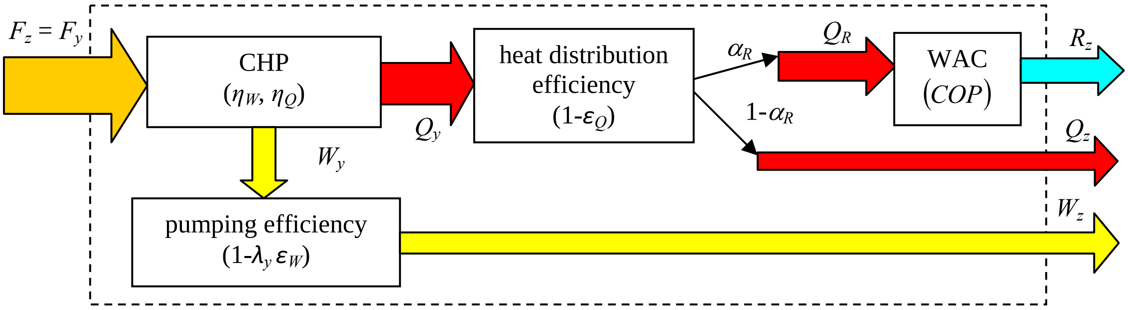


Figure 1. Energy flow model in a distributed trigeneration plant with CHP, DHN and WAC.

thermal losses due to the heat network, it can be written:

$$Q_y\,(1-\varepsilon_Q) = Q_R + Q_z = \\ = \alpha_R\left(1-\varepsilon_Q\right)Q_y + \left(1-\alpha_R\right)\left(1-\varepsilon_Q\right)Q_y \tag{6}$$

Then, on the basis of the definition of the cogeneration efficiencies in (1), the fuel thermal input $F_z = F_y$ can be expressed in different forms, looking at the output-to-input paths connecting each one of the three energy outputs from the trigeneration system to the unique fuel input, namely:

$$F_z = \frac{Q_y}{\eta_Q} = \frac{Q_z}{\left(1-\alpha_R\right)\left(1-\varepsilon_Q\right)\eta_Q} \tag{7}$$

$$F_z = \frac{W_y}{\eta_W} = \frac{W_z}{\eta_W - \varepsilon_W \eta_Q} \tag{8}$$

$$F_z = \frac{R_z}{\alpha_R COP\left(1-\varepsilon_Q\right)\eta_Q} \tag{9}$$

On these bases, the *TCO2ER* indicator (5) becomes:

$$TCO2ER = 1 - \frac{\mu_F}{\mu_W^{SP}\cdot\xi + \mu_Q^{SP}\cdot\eta_Q\left(1-\alpha_R\right)\left(1-\varepsilon_Q\right)} \tag{10}$$

where $\xi = \left(\eta_W - \varepsilon_W\ \eta_Q\right) + \alpha_R \dfrac{COP}{COP^{SP}}\left(1-\varepsilon_Q\right)\eta_Q$.

The *TCO2ER* model in (10) yields an analytical formulation of the potential emission reduction in trigeneration as a function of the plant component and network-related efficiencies, the splitting factor, and the emission factors for the input fuel and the SP references. Therefore, it is possible to run various analyses to highlight the role played by the specific entries involved in the study, as shown in the following section.

## IV. NUMERICAL APPLICATIONS

### A. Energy System Description

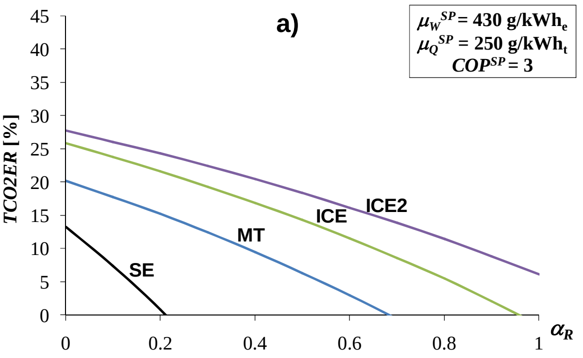
Different equipment typologies available for small-scale applications are considered, namely, an SE coupled to an adsorption chiller, and a MT and two ICE coupled to a single-effect absorption chiller. The average performance characteristics (assumed to be constant and equal to nominal values, for the sake of simplicity) and typical capacities for the equipment analysed are shown in Table I. In addition, also average energy penalties due to heat networks are considered, with heat losses increasing with the CHP typology and size, assuming that larger heat networks are subsequently needed. The pumping electrical parasitic losses are instead assumed equal to 1% in all cases. For SE, no DHN connection is considered. All CHP systems are natural gas-fuelled.

The *TCO2ER* indicator is plotted in Figure 2 assuming $\alpha_R$ as the independent variable. Two cases are analysed:

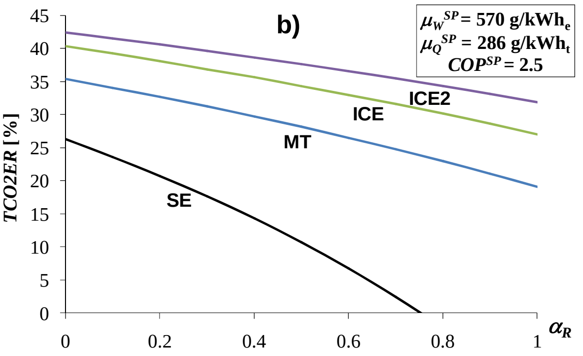
- Case 1): The SP emission factor for electricity refer to average emissions in UK ($\mu_W^{SP}$ = 430 g/kWh$_e$) [3], while the heat-related emission factor is calculated assuming average boilers with efficiency $\eta_Q^{SP}$ = 0.8, fed on natural gas, thus obtaining $\mu_Q^{SP} = \mu_F / \eta_Q^{SP}$ = 250; finally, for the reference chiller $COP^{SP}$ = 3; the results are shown in Figure 2a.
- Case 2): peak ("marginal plant") emissions for the UK power system (570 g/kWh$_e$) [3] are considered, also introducing lower (with respect to case 1) average efficiency values for boilers (0.7) and chillers (2.5); the results are reported in Figure 2b.

TABLE I. AVERAGE CAPACITY AND EFFICIENCY VALUES FOR SMALL-SCALE DISTRIBUTED TRIGENERATION SYSTEM EQUIPMENT

| | capacity [kW$_e$] | $\eta_W$ | $\eta_Q$ | *COP* | $\varepsilon_Q$ | $\varepsilon_W$ |
|---|---|---|---|---|---|---|
| SE | 3 | 0.1 | 0.75 | 0.4 | 0 | 0 |
| MT | 100 | 0.3 | 0.5 | 0.7 | 0.01 | 0.01 |
| ICE | 1000 | 0.35 | 0.5 | 0.7 | 0.03 | 0.01 |
| ICE2 | 5000 | 0.4 | 0.45 | 0.7 | 0.05 | 0.01 |



a) *average* UK emissions



b) *peak* UK emissions

Figure 2. $CO_2$ emission reduction for small-scale trigeneration systems.

### B. Discussion and Comments on the Numerical Results

The analysis presented has been carried out by using only the parameters of the CCHP systems and of the SP equivalents, with no need to specify the amount of electricity, heat and cooling involved. The rationale of this procedure is that the emissions reduction depends only on the contribution of the trigeneration systems in efficiently displacing SP of the various energy vectors needed. In the energy system, the possible excess of demand of any energy vector is covered by external supply coming from the additional components in place (that is, the electricity distribution grid for electricity, boilers for heat and electric chiller for cooling; these components are not explicitly shown in Figure 1), whose characteristics are the same as the ones assumed for the corresponding separate production equivalents. The analysis based on the *TCO2ER* indicator then refers to the effectiveness of displacing part of the SP with trigeneration, for the same amount of the energy demand supplied through the trigeneration chain shown in Figure 1. For instance, when $\alpha_R = 0$ there is no cooling demand supplied through the trigeneration chain, meaning that any cooling demand is covered by electric chillers with parameter $COP^{SP}$ supplied by the electrical network with equivalent emission factor $\mu_W^{SP}$. Likewise, for $\alpha_R = 1$ there is no trigenerated heat, and the entire heat demand is conventionally covered by boilers with equivalent emission factor $\mu_Q^{SP}$. The amounts of energy not provided by the trigeneration system are then excluded from the analysis.

From Figure 2, when operating in electricity and heat cogeneration mode ($\alpha_R = 0$), all the technologies considered bring $CO_2$ emission reduction with respect to the base case references, increasing with the electrical efficiency (and size). The emission reduction potential for CCHP systems decreases with increasing $\alpha_R$. The cooling production through thermal power in a WAC, in fact, although from wasted heat, is energetically inefficient compared with a relatively higher-efficiency reference electric chiller. Thus, it is more environment-effective to cogenerate heat and electricity ($\alpha_R = 0$) than cogenerating cooling and electricity ($\alpha_R = 1$). In particular, considering *average* UK emission intensities (Figure 2a), the emission reduction becomes negative beyond a certain $\alpha_R$, whose values increases with the CHP electrical efficiency (and size). More specifically, an SE coupled to an adsorption chiller proves to be ineffective in terms of $CO_2$ emission reduction already for $\alpha_R$ above 0.2. The environmental performance is instead much better if the CCHP systems are compared to *peak* UK emissions (Figure 2b: for the various technologies, the emission reduction almost doubles for $\alpha_R = 0$ and even triplicates for $\alpha_R = 1$ with respect to the average baseline reference. In this case, the MT and the two ICE, coupled to absorption chillers, could bring emission reductions of the order of 20% to 40% in the whole range of $\alpha_R$, while the SE would bring benefits for $\alpha_R < 0.75$.

The environmental evaluation of CCHP systems is strongly affected by the selection of the *reference* scenario. What rationale is more correct to adopt in terms of baseline reference may be policy matter. In particular, it is possible to argue that DG is likely to displace marginal plant operation [3], since renewables and nuclear plants are usually operated with the flattest possible profile. In addition, in a deregulated environment it is often tough to figure out what plants are being offset, with older coal plants that may be preferred to newer gas plants on the basis of economic reasons. In any case, marginal power plants are the most likely to be displaced by CCHP systems producing cooling power in the summer peak hours. In addition, the actual efficiency of boilers may be much less that the rated one, above all in the summertime, as assumed when drawing the picture in Figure 2b. On the other hand, an average generation mix reflects, somehow, the more decarbonised future UK and several European countries are committed to. However, in the next years also CCHP efficiencies are expected to improve, so that again the overall emission reduction resulted from distributed trigeneration could be of the order of magnitude of the ones obtained for marginal plant operation.

In order to highlight the effectiveness of CCHP introduction in various countries, a further analysis has been made by considering the potential emission reductions an ICE2 (the technology leading to the highest $CO_2$ emission reduction among the ones tested above) could bring in different jurisdictions or national contexts, considering the emission factors referring to average specific emissions. For this analysis the *TCO2ER* equation (10) has been used by changing the value of average specific emissions $\mu_W^{SP}$ and maintaining the same values for $\mu_Q^{SP}$ and $COP^{SP}$. In addition to the UK case already shown (with $\mu_W^{SP}$ = 430 g/kWh$_e$), the values considered, taken from [19][22], refer to Norway ($\mu_W^{SP}$ = 3 g/kWh$_e$), France ($\mu_W^{SP}$ = 78 g/kWh$_e$), the former EU15 ($\mu_W^{SP}$ = 362 g/kWh$_e$), and Italy ($\mu_W^{SP}$ = 525 g/kWh$_e$). Figure 3 shows the relevant results.

It is conceptually evident that trigeneration can be more effective in jurisdictions with higher electricity-related specific emissions. However, *TCO2ER* analysis provides clear emission reduction quantification in the various contexts. The application of the same technology (ICE2) with the purpose of reducing $CO_2$ appears to be effective in Italy and UK for every usage (*i.e.*, for any value of $\alpha_R$), while it would never be effective in Norway or France. The results for EU15 are of course of an intermediate nature. However, EU15 specific emissions are obtained by averaging out values referring to very different jurisdictions. The use of an overall value masks the possible benefits in jurisdictions with prevailing fossil fuels, as well as the total inadequacy of putting natural gas-supplied trigeneration systems in other jurisdictions with almost $CO_2$ emission-free electricity production. This confirms how making global averages in very heterogeneous contexts can lead to results that are not useful for any of the individual communities.

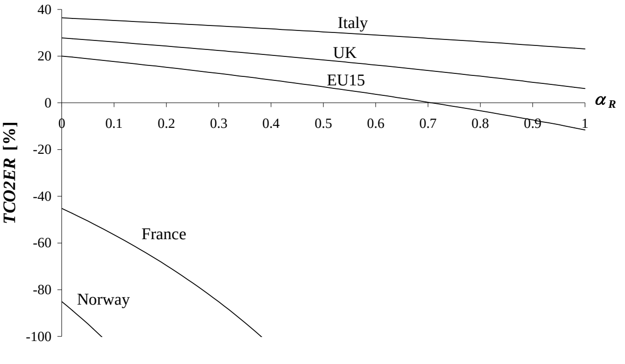


Figure 3. Effectiveness of $CO_2$ emission reduction by using ICE2 in different national contexts.

## V. FINAL REMARKS AND FUTURE WORKS

In the development of energy systems with enhanced energy efficiency and environmental performance, the exploitation of distributed multi-generation systems based on combined generation of multiple energy vectors is a particularly significant and promising option.

This paper has introduced a general analytical model based on black-box representations for $CO_2$ emission reduction assessment from distributed trigeneration (as well as cogeneration) systems, in case coupled to heat networks. Dedicated assessment of the carbon dioxide reductions that can be obtained from the deployment of such trigeneration systems has been performed by comparing the trigeneration systems outcomes that satisfy the energy demand of different energy vectors with the separate production baseline references to supply the same demand of the corresponding energy vectors. In particular, the numerical analyses have been focused on small-scale energy systems currently available in the market.

The results show that consistent benefits can be obtained when the reference case points to marginal generation in UK, that is, the one most likely to be displaced by DG systems. Electrical efficiency, which is also a function of the plant size, plays a key role in the overall assessment, while the losses due to heat network affect marginally the results. Hence, micro-CHP Stirling engines prove to be the least effective, mainly due to their low electrical efficiency. The emission reduction performance is also a function of the quota of cogenerated heat feeding the chillers. With the cooling equipment considered here, in general the emission reduction decreases if the cogenerated heat firing the chiller increases. Although trigeneration allows for potential recovery of otherwise wasted heat, negative emission reduction (i.e., emission increase) could arise in certain operation points, also depending on the baseline reference. This assessment should be carried out at the planning stage, in order to avoid the setup of environmentally inefficient solutions.

The analysis has then been extended to show that the same trigeneration technology can be effective in certain jurisdictions characterized by fossil fuels in the energy mix used to supply the national electricity generation system, while it may exhibit total inadequacy of being adopted in other jurisdictions in which fossil fuels are almost unused.

The analyses presented here are meant to be a preliminary assessment of the potential emission reduction from distributed multi-generation systems. In particular, further analyses are in progress, including more detailed models of heat networks, and based on time-domain simulations that take into account load variations and actual operating conditions for all the equipment. In addition, the environmental benefits of different distributed energy solutions are to be assessed against their cost effectiveness and their impact on the electrical network. This may also require sensitivity studies on the underlying economic assumptions, such as the fuel and electricity rates, as well as analysing the possibility of operating CCHP systems within microgrids.

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