Energy and CO_2 emission assessment of cooling generation alternatives: A comprehensive approach based on black-box models

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Abstract: - Nowadays, cooling production is increasingly required to satisfy more and more demanding life standards, in particular for air conditioning applications in urban areas. Energy efficiency improvement and greenhouse gas emission reduction are primary tasks at the present stage of evolution of the energy generation systems. In this respect, different alternatives available for cooling generation, fed either electrically or by gas (absorption or engine-driven chillers), can bring about different environmental impacts in dependence on the specific generation framework. This paper presents a comprehensive unified energy and environmental model for cooling generation assessment. The approach proposed is based upon formulation of synthetic black-box models that characterize the relevant energy system components. Specific indicators are defined to represent the cooling energy saving and CO_2 emission reduction obtainable from natural gas direct-fired chillers with respect to traditional compression electric chillers. By using these novel indicators, break-even conditions are worked out to identify the limits of convenience of different cooling generation technologies. Numerical examples are provided to assess the potential benefits of the various solutions in different countries. Specific discussions refer to considering power system average or marginal operational characteristics.

Key-Words: - Absorption chillers, Compression chillers, Electric chillers, Emission reduction, Energy saving, Engine-driven chillers, Environmental impact assessment, Greenhouse gases, Natural gas.

A. Acronym list

CEC	Compression Electric Chiller
CHR	Cooling Heat Rate
COP	Coefficient Of Performance
DFC	Direct-Fired Chiller
EDC	Engine-Driven Chiller
GAC	Gas Absorption Chiller
LHV	Lower Heating Value
CCO2ER	Cooling CO_2 Emission Reduction
CPES	Cooling Primary Energy Saving

B. Symbols

Energy vectors:
W=electricity [kWh_e]
F= fuel thermal energy content [kWh_t], *LHV*-based
R=cooling energy [kWh_c]

η = efficiency
μ=dispatch factor
m=mass.

Subscripts represent energy sources or end use, and specify the measuring units: c=cooling, e=electricity, t=thermal.
Superscripts indicate energy vectors or equipment.

1 Introduction

The development of new technologies for energy generation is consistently being boosted in the last years, in response to ever more stringent issues related to generation efficiency and greenhouse gas emission reduction. In this outlook, the steadily increasing need for cooling power generation for air conditioning applications has pushed towards the development of various chiller technologies. Hence, along with the widespread *Compression Electric Chillers* (CECs), other updated equipment is nowadays available for cooling power generation. In particular, *Direct-Fired Chillers* (DFCs), in which a certain fuel, typically natural gas, represents the direct energy input to the cooling generation plant, may be viable alternatives, also depending on the specific economic framework.

Among DFC solutions, *Gas-fed Absorption Chillers* (GACs) and *Engine-Driven Chillers* (EDCs) [1-4] are technologies recently gaining important market shares. Actually, absorption chillers have been traditionally adopted as *indirect-fired*, above all for exploiting waste heat available from industrial processes or from cogeneration systems. This has led to set up high-efficiency and cost-effective trigeneration systems for the combined production of electricity, heat and cooling [2,5]. However, the economics of cooling generation, within a multi-generation plant [6,7] or for sheer air-conditioning applications, is strongly influenced by fuel and electricity prices [8,9]. Hence, GACs may often be adopted as an alternative to CECs, above all for relatively high electricity-to-gas rate ratios [1,3,8,9]. Likewise, EDCs are compression chillers whose compressor is directly driven mechanically by a fuel-fired engine (normally, natural gas is the adopted fuel), rather than by an electrical motor. Hence, besides the economic aspect, better energy performance could be obtained owing to avoiding the intermediate step of generating electricity from fuel and finally converting into cooling power. In addition, EDCs can be often used for cogeneration of heating and cooling, since large amount of heat can be recovered from the engine exhaust gases, as in conventional cogeneration systems, thus increasing the energy system efficiency and economics [4,10,11]. However, in the sequel of the paper, dedicated to cooling model analysis, we will focus on the cooling-only characteristics of an EDC.

From a more technical point of view, there is a potentially growing interest towards direct-fired chillers (both GACs and EDCs) due to power grid vulnerability issues. In fact, the increasing demand of air conditioning worldwide has brought about higher and higher power flows in the electrical grid, up to causing congestions and black-outs [12]. In this respect, cooling generation from DFCs occurs *locally*, on the user's site, so that it avoids a certain amount of electricity flowing in the grid, reducing the risk of congestions and black-outs, as well as reducing transmission and distribution losses. Under this perspective, the shift from electricity-driven chillers to gas-driven chillers could have a similar impact as distributed generation technologies are having on distribution networks [13,14]. In fact, DFCs contribute to reduce the electrical network loading by decreasing the quota of electricity that would be needed for cooling generation in conventional CECs. This aspect can be framed within a more general model of transformation from a given form of demand (for instance cooling) into a certain form of network energy vector, such as electricity or gas [7].

In addition, further economic benefits may take place if cooling power is generated through DFCs, since air conditioning is mostly needed in the electricity peak hours (central hours of summertime days). Of course, increasing diffusion of gas-fed chillers could consistently increase the flows in the gas transmission and distribution systems, as a consequence of the load shifting phenomenon mentioned above. However, in many countries the gas network is normally sized on the winter loading, when the request for natural gas for heating is the highest, and difficultly the gas request for air conditioning in the summertime could overcome the gas demand occurring in winter.

Besides electrical load relief and potential economic benefits, GACs and EDCs can exhibit good primary energy performance. In particular, triple-effect absorption chillers are recently being developed and commercialized, allowing for better performance than double-effect chillers [1,2]. Likewise, last-generation EDCs [1,2,4] exhibit excellent characteristics. As a consequence of the high performance, DFCs could also bring CO_2 emission reduction with respect to CECs, also owing to the relatively low carbon content of natural gas with respect to other fossil fuels [1,15].

The energy scenario in the last years is being more and more driven by the search for lower environmental impact technologies, so that the diffusion of DFCs will depend consistently on the possibility of displacing higher CO_2 emission intensity energy systems. More specifically, this strongly depends on the fuels and power plant typologies, and on the mix used for electrical generation in a given country. From this standpoint, few studies are available to model and compare the environmental characteristics of conventional energy systems (and the power system, in particular) to high-efficiency and relatively newer technologies such as trigeneration systems [16-19]. In addition, in [20] a general model introducing equivalent energy and environmental efficiencies for comparison of different generation alternatives for various energy vectors is presented. The reference [1] runs some analyses regarding the primary energy implications of adopting DFCs or CECs in given energy scenarios. However, no reference is available to clearly model and synthesize the factors that, in a given power system, determine whether emerging DFCs can be effectively adopted for energy saving and greenhouse gas emission reduction with respect to conventional CECs.

On these premises, in this paper a comprehensive approach for assessing the energy and CO_2 emission performance of DFCs as opposed to CECs is presented. More specifically, the approach proposed is based upon *black-box* energy and emission models of the various equipment typologies involved in the analysis. Equivalent energy and emission indicators are formulated so as to highlight the identical formal structure of the energy and emission model introduced. In particular, it is underlined how, besides the energy performance characteristics of the chillers, the emission factor for electricity generation [16,17] plays a key role in the analysis. In this respect, specific case study applications based upon energy and emission break-even analyses are run in order to comparatively assess the effectiveness of adopting CECs rather that GACs or EDCs with various performance characteristics. In addition, the suitability of adopting different cooling generation solutions for energy saving and CO_2 emission reduction is assessed for different countries, with reference to their actual generation framework.

The paper is structured as follows. Section 2 describes the energy and CO_2 emission black-box models for the considered chiller typologies. Section 3 introduces energy saving and emission reduction indicators specifically developed for comparing DFCs to CECs. Section 4 contains various numerical applications that make reference to both general parametric analyses and more specific calculations relevant to actual generation environments in different countries with chillers currently available on the market. The last section contains the final remarks and introduces future works.

2 Energy and CO_2 emission black-box modeling for chiller alternatives

2.1 Energy characteristics

The energy performance of cooling generation equipment is described by means of the relevant *COP* (Coefficient Of Performance), ratio of the desired output (cooling energy, usually in the form of chilled water) R to the relevant input. More specifically, the energy input can be electricity W_c for electric chillers, or *LHV*-based fuel thermal energy F_c for direct-fired GACs and EDCs [1,3,4]:

$$COP^{CEC} = \frac{R}{W_c} \tag{1}$$

$$COP^{DFC} = COP^{GAC} = COP^{EDC} = \frac{R}{F_c} \tag{2}$$

where the subscript c points out that the final use of the relevant input is *cooling* production.

The expression (2) indicates the same energy performance model for DFCs (EDCs and GACs). Indeed, although the components and the thermodynamics of the two chiller typologies are different, seen from the outside, that is, focusing on the input-output energy flows, it is possible to model them in the same fashion. This gives origin to the *input-output black-box* modelling approach, according to which the energy flows are characterized by input-output *synthetic* information (in this case, the *COP*), without entering into the details of describing the internal structure, energy flows and thermodynamics. Of course, the information related to the *COP* must be detailed enough to properly model the actual characteristics of the various chiller typologies. In this respect, in general the chiller performance depends upon the technology, the condenser typology (in particular, if water-cooled or air-cooled), the size (performance is usually better for bigger chillers), the outdoor conditions (above all for air-cooled chillers), the temperature of the ambient to keep cooled, and the loading level [1,4,21]. Hence, given the specific chiller, information relevant to all these variables is needed in order to adequately evaluate, numerically, the "simple" models (1) and (2).

Being the black-box model for GACs and EDCs the same (formula (2)), in the sequel only expressions generally related to DFCs will be formulated. However, they must be considered to be applicable to both an EDC and a GAC. Of course, apart from the structure of the performance indicator, the numerical values for COP^{EDC} and COP^{GAC} are different, depending on all the variables mentioned above.

2.2 The Cooling Heat Rate (*CHR*) model

The expressions (1) and (2) refer to different energy typology inputs, so that a numerical comparison between them would be incorrect. Hence, for energy analysis it is more suitable to refer the relevant cooling output to a common input, which in the specific case can be represented by the original primary energy (fuel energy content) needed to generate cooling. In this outlook, while for DFCs the relevant input is already primary energy delivered when burning natural gas, for CECs an intermediate step is needed, in order to transform the electricity input back into the original fuel energy needed to produce it. Hence, it is possible to introduce, in turn, an input-output black-box model also for the *equivalent power plant* turning fuel input into electrical output, characterized by a classical electrical efficiency η_e [15]. In particular, this equivalent power plant could represent a black-box model of the average power system in a given country. In this case, the numerical value of η_e should also take into account average electrical transmission and distribution losses due to the fact that the bulk of electrical energy is usually generated in power plants far from the cooling user.

On these premises, it is straightforward to formulate a common-ground energy comparison between the two different typologies. In fact, the CEC black-box and the equivalent power plant black-box can be aggregated together to set up a further black-box model, with fuel as overall input and cooling as final output. Hence, it is possible to compare CECs and DFCs by introducing the relevant Cooling Heat Rate (*CHR*) [5], defined as primary energy to cooling energy ratio:

$$CHR^{CEC} = \frac{W_c/\eta_e}{R} = \frac{1}{\eta_e \cdot COP^{CEC}} \quad (3)$$

$$CHR^{DFC} = \frac{F_c}{R} = \frac{1}{COP^{DFC}} \quad (4)$$

The expression (3) characterizes the fuel-cooling black-box model for CECs, while the expression (4) models the two typologies of DFC considered here, namely, GACs and EDCs. Assessment of the relevant *CHRs* requires only the energy characteristics of the energy system components involved in the analysis. This formulation in terms of heat rates allows for unbiased estimation of the primary energy needed to produce a certain amount of cooling energy by means of the three different chiller typologies, as illustrated in the sequel.

2.3 CO_2 emission characteristics

A suitable approach to model and characterize the emissions of a given pollutant (and in particular CO_2) from generic combustion devices is represented by the output-related *emission factor*, defined according to the expression:

$$m^X = \mu^X \cdot X \quad (5)$$

In (5), m^X is the mass of CO_2 emitted while generating the useful energy output *X*, and μ^X is the relevant *emission factor*, that is, the *specific mass emissions* of CO_2 per unit of *X*, in [g/kWh]. The emission factor model is usually applied for assessing power plants or heat generators. However, it can be readily extended also to assess the environmental performance of different cooling generation equipment. More specifically, it is possible to follow a black-box approach coherent with the *CHR* definitions in Section 2.2. Hence, the CO_2 emissions from a GAC or an EDC can be evaluated on the basis of the specific emissions μ^F related to the fuel thermal energy F_c, input to the absorption chiller. This input-related emission factor can be estimated with good approximation as a function of the characteristics of the chemical reaction, and thus of the fuel only [15-17]. Hence, it is possible to assume μ^F for a given fuel constant for different operational conditions. Therefore, taking into account (2) and (5), the energy output-related specific emissions (mass of CO_2 emitted per unit of cooling energy *R* produced) for a DFC can be evaluated as

$$\mu^R = \frac{\mu_c^F}{COP^{DFC}} = \mu_c^F \cdot CHR^{DFC} \quad (6)$$

in case accounting for off-design models for COP^{DFC}.

Similarly to the approach followed for the emission characterization of a GAC or an EDC, the specific emissions related to cooling generation from an electric chiller can be assessed, considering (1) and (5), starting from the average emission factor μ^W for electricity generation from a given equivalent power plant:

$$\mu^R = \frac{\mu^W}{COP^{CEC}} \quad (7)$$

Thus, also for a CEC it is possible to assess the CO_2 emission factor passing by the specific *COP* off-design models, in case. In alternative to the expression (7), the cooling-related emission factor for electric chillers can be assessed with reference to the equivalent power plant fuel input, in analogy to (6):

$$\mu^R = \frac{\mu^W}{COP^{CEC}} = \frac{\mu_e^F}{\eta_e \cdot COP^{CEC}} = \mu_e^F \cdot CHR^{CEC} \quad (8)$$

Both expressions (6) and (8) can be formulated in terms of cooling heat rates as defined above, and thus reflect the black-box modeling approach. Graphical visualization of the proposed formulation is illustrated in Fig. 1 and Fig. 2 for DFCs and CECs, respectively.

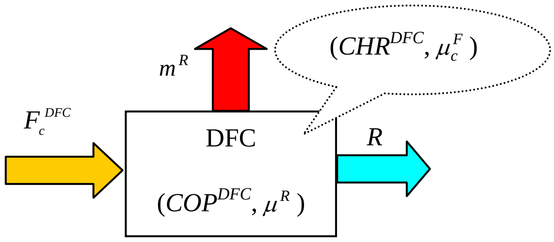

Fig. 1. Black-box model for energy and environmental assessment of direct-fired chillers.

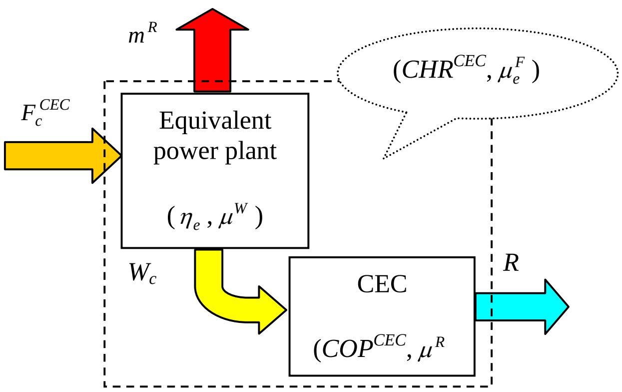

Fig. 2. Black-box model for energy and environmental assessment of electric chillers.

3 Cooling energy saving and CO_2 emission reduction indicators

3.1. Cooling Primary Energy Saving (*CPES*)

Let us consider a certain amount of cooling energy R, which can be generated in a GAC or an EDC from a certain fuel thermal input F_c, or in a conventional CEC from a certain electrical input W_c. Referring the generation of the cooling energy R to primary energy, from Fig 1 and Fig. 2 it possible to write

$$F_c^{CEC} = CHR^{CEC} \cdot R \tag{9}$$

$$F_c^{DFC} = CHR^{DFC} \cdot R \tag{10}$$

Therefore, it is possible to define a *Cooling Primary Energy Saving* (*CPES*) indicator, assessing the relative energy saving brought by adopting a DFC with respect to a "classical" CEC, as

$$CPES = \frac{F_c^{CEC} - F_c^{DFC}}{F_c^{CEC}} = 1 - \frac{1}{\dfrac{COP^{DFC}}{\eta_e \cdot COP^{CEC}}} = 1 - \frac{CHR^{DFC}}{CHR^{CEC}} \tag{11}$$

In particular, positive values of the *CPES* (11) indicate higher energy profitability of a DFC for producing cooling energy under specific conditions.

3.2 Energy break-even analyses

On the basis of the expression (11), it is possible to work out the energy break-even condition as

$$\hat{COP}^{DFC} = \eta_e \cdot COP^{CEC} \tag{12}$$

according to which there will be energy saving brought by adopting a DFC for COP^{DFC} values higher than (12), that is, for:

$$COP^{DFC} > \hat{COP}^{DFC} \tag{13}$$

Once given the characteristics of the electrically-based cooling generation means, on the basis of (12) and (13) it is possible to run parametric analyses to assess the potential energy benefits from adopting a direct-fired chiller, as exemplified in Section 4.1.

3.3 Cooling CO_2 Emission Reduction (*CCO2ER*)

The comparative energy analysis between GACs or EDCs and CECs is related to the relevant efficiencies involved, that is, to the *CHR* for a DFC and a CEC, as apparent from (11). In the same light, the comparative CO_2 emission assessment is a function of the electricity-related emission factor μ^W of the equivalent power plant for electricity generation (input to the CEC) (Fig. 2) and of the fuel-related emission factor μ_c^F for the input to the DFC (Fig. 1). In fact, given the same amount R of cooling energy produced by a GAC or an EDC and a CEC, on the basis of (1) and (2), and taking into account the general definition (5), it is possible to write for a DFC (Fig. 1)

$$\left(m^R\right)^{DFC} = \left(\mu^R\right)^{DFC} \cdot R = \frac{\mu_c^F}{COP^{DFC}} \cdot R \tag{14}$$

and for a CEC (Fig. 2)

$$\left(m^R\right)^{CEC} = \left(\mu^R\right)^{CEC} \cdot R = \frac{\mu^W}{COP^{CEC}} \cdot R \tag{15}$$

Hence, in analogy to the *CPES* indicator (11), it is possible to introduce the *Cooling CO_2 Emission Reduction* (*CCO2ER*) indicator for assessing the emission reduction brought by adopting a DFC as opposed to a CEC:

$$CCO2ER = \frac{\left(m^R\right)^{CEC} - \left(m^R\right)^{DFC}}{\left(m^R\right)^{CEC}} = 1 - \frac{\left(\mu^R\right)^{DFC}}{\left(\mu^R\right)^{CEC}} = 1 - \frac{\mu_c^F \cdot COP^{CEC}}{\mu^W \cdot COP^{DFC}} \tag{16}$$

The expression (16) is formally similar to (11), with the emission factors substituting the cooling heat rates. In addition, the electricity-related emission factor can be explicitly considered in (16), yielding

$$CCO2ER = 1 - \frac{\mu_c^F \cdot COP^{CEC}}{\mu_e^F \cdot \eta_e \cdot COP^{DFC}} = 1 - \frac{\mu_c^F \cdot CHR^{DFC}}{\mu_e^F \cdot CHR^{DFC}} \tag{17}$$

The expression (17) highlights the role of the fuel typology used as input for electricity generation and for firing the absorption chiller or the engine-driven chiller. In fact, with respect to (11) in which only the primary energy is relevant, in (17) the emission factors appear as weight to the cooling heat rates. In particular, if the same fuel (natural gas, in this specific case) is used as input to the equivalent power plant and to the direct-fired chillers, the expression (17) coincides with the expression (11). Indeed, according to the emission model discussed in Section 2.3, energy saving and emission reduction expressed in relative terms bring the same numerical value.

3.4 CO_2 emission break-even analyses

As for the energy assessment, it is possible to carry out a CO_2 emission break-even assessment based on the expressions (16) and (17). More specifically, it is possible to formulate some relevant indicators that make the analysis straightforward and point out the major variables involved. In particular, as apparent from the models developed in Section 2, on the one hand the CO_2 emission source in the GAC or an EDC is directly represented by the fuel input. On the other hand, with the aim of comparing the chiller alternatives with respect to the *status quo* or possible scenarios of electricity generation in a certain region (as for instance done in [16-18] for trigeneration systems), the key driver in the analysis turns out to be the CO_2 average emission from electricity generation. On these premises, from (16) the CO_2 emission *break-even* condition (*CCO2ER* = 0) between the production in CECs and DFCs can be expressed as

$$\overline{COP}^{DFC} = COP^{CEC}\,\frac{\mu_c^F}{\mu^W} \qquad (18)$$

and the condition for obtaining positive CO_2 emission reduction from a DFC is

$$COP^{DFC} > \overline{COP}^{DFC} \qquad (19)$$

Given the symmetry highlighted above with the energy saving problem, this approach allows for carrying out analyses formally identical to the ones outlined in Section 3.2. In particular, the relevant break-even emission problem is formulated in terms of an equivalent *COP* that, fixed the fuel adopted for firing the DFC (namely, natural gas), is a function of only COP^{CEC} and μ^W. Therefore, it is possible to run parametric analyses that estimate the profitability of adopting different cooling generation equipment within different power systems with different values of μ^W (Section 4.2).

3.5 Analysis benchmarks: state-of-the-art, average or marginal plants?

When running comparative studies between DFCs and CECs, the numerical data to assign to the electricity generation CO_2 emission intensity and equivalent efficiency (Fig. 2) is particularly relevant to the assessment outcomes. Indeed, to establish which efficiency and emission values could represent the most appropriate benchmark is not straightforward. In particular, as mentioned in the introduction, when DFCs displace conventional CECs they impact in a similar fashion as DG impacts on the electrical network. Hence, in analogy to what discussed for cogeneration and more generally multi-generation systems [19,20], different rationales can be adopted to evaluate the avoided depletion of primary sources and emissions. More specifically, the following approaches could be typically undertaken:

a) DFCs are assumed to displace CECs fed by *state-of-the-art* thermal power system generation, so that CHR^{CEC} and μ^W are assessed with reference to, for instance, a gas-fired combined cycle power plant, today's best technology, with η_e of the order of 0.5, comprehensive of transmission and distribution losses.
b) DFCs are assumed to displace *average* power system generation, so that average values from the overall power plant mix in a given area or country are used for estimate of CHR^{CEC} and μ^W.
c) DFCs are assumed to displace *marginal* (or *peak*) power system generation, so that CHR^{CEC} and μ^W are related to the characteristics of the marginal power plants coming into operation on the basis of specific optimal dispatching (or, in case, market-driven merit order) procedures. For instance, low-efficiency coal plants could represent marginal plants in several countries.

Numerical applications relevant to these approaches are provided in Section 4.

On top of all these alternative rationales, when assessing CO_2 emissions from power systems a further decision variable could be related to making reference to thermal power plants only (as in the energy saving analysis), or to including in the analysis also the quota of renewable sources. Indeed, renewable sources might play a prominent role in certain power systems, by pulling down consistently the overall CO_2 emissions. This applies in particular to power systems relying consistently on wind, hydro and nuclear systems.

4 Numerical applications

4.1 Energy break-even calculations

With reference to the concepts introduced in Section 3.2, Fig. 3 shows different energy break-even curves with $\hat{COP}^{DFC}$ (12) in function of the electric chiller

COP, with the equivalent power plant electrical efficiency as the curve parameter. In addition, for the sake of comparison, also typical *COP* values for single-effect (rarely used as direct-fired), double-effect and triple-effect GACs are shown. Concerning EDCs, typical average values of COP^{EDC} can be estimated to be similar to or even slightly higher than for triple-effect absorption chillers.

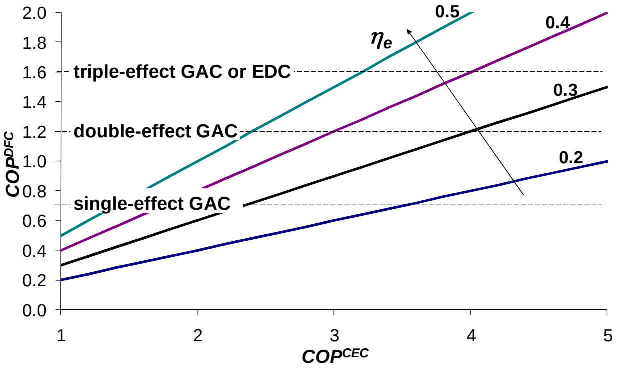

Fig. 3. Energy break-even characteristics.

With reference to a "classical" double-effect GAC with *COP* of about 1.2, let us for instance consider a comparison according to the approach b) in Section 3.5, namely, the equivalent power plant electrical efficiency is set to 0.4 (about the average efficiency from thermal power plant production in Italy, considering about 7% of transmission and distribution losses). In this case, the GAC can compete with an electric chiller if COP^{CEC} is lower than 3. This is a value normally reached by small-scale (below 1 MW_c) chillers for centralized air conditioning, while household-size air conditioning units usually do not reach this performance level. However, even the performance of a centralized chiller depends on various conditions, and in particular on the outdoor temperature, above all if air-cooled [1,4,21], as often occurs in urban areas. Hence, double-effect GACs can also be competitive for centralized applications in case the chiller is constrained to operate under severe outdoor conditions. In this case, in fact, it could be profitable to adopt a double-effect absorption chiller instead of an electric one. The convenience in this sense might as well occur in the presence of lower-efficiency equivalent power plants, such as centralized coal or oil or gas turbine-based plants, as well as small-scale distributed generation prime movers, with efficiency normally lower than 0.4. This kind of analysis would correspond to adopt the approach c) outlined in Section 3.5. Instead, if adopting a combined cycle (η_e about 0.5, a figure that also takes into account typical transmission and distribution losses) for electricity production (corresponding to the approach a)), a double-effect chiller could be competitive only with respect to a CEC with *COP* lower than 2.5. Adopting a triple-effect GAC, with a *COP* higher than 1.5, would allow for higher benefits. For instance, considering again η_e = 0.4, there would be energy convenience for a GAC with respect to a CEC with COP^{CEC} as high as about 4. The same considerations hold true for EDCs, whose average performance values are about 1.5 or higher. Single-effect chillers, instead, can barely be energy-competitive in correspondence of average values for COP^{CEC} and electrical efficiencies in most countries worldwide. Hence, their utilization should be related to waste heat recovery, for instance from cogeneration systems, so as to set up trigeneration systems.

4.2 CO_2 emission break-even calculations

In analogy to the energy efficiency analyses run in Section 4.1, Fig. 4 shows different emission break-even $\overline{COP}^{DFC}$ (18) curves as a function of the electric chiller *COP*, with the electricity-related emission factor for the equivalent power plant (in g/kWh_e) as the curve parameter. The CO_2 emission factor for natural gas, with reference to the *LHV*, is assumed equal to 200 g/kWh_t [15]. In addition, as for Fig. 3, for the sake of comparison also typical *COP* values for single-effect, double-effect and triple-effect GACs are shown in Fig. 4. Again, the performance of EDCs is similar to the performance of triple-effect GACs.

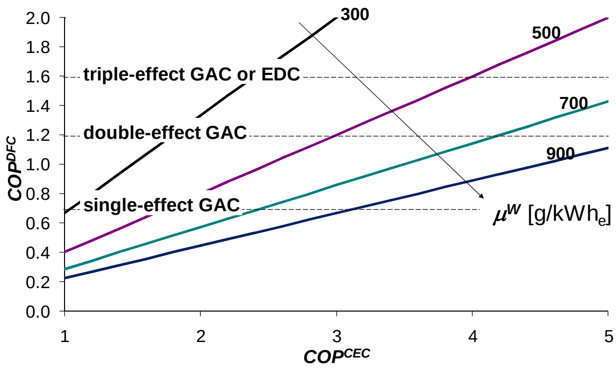

Fig. 4. CO_2 emission break-even characteristics.

As a term of comparison, it is possible to consider that the average emission factor for electricity produced from thermal power plants in Italy (approach b)) is about 700 g/kWh_e (also entailing transmission and distribution electrical losses). In this case, a double-effect GAC would be competitive, in terms of CO_2 emissions, if compared to a CEC with COP^{CEC} lower than about 4.2; a triple-effect GAC or an EDC would bring about emission reduction for COP^{CEC} lower than about 4.8. Hence, absorption chillers and EDCs could be emission-efficient for a wide range of applications and conditions, in comparison with CECs fed by electricity produced in thermal power plants. However, as discussed in Section 3.5, an alternative analysis should consider that a share of the overall electricity generation in a power system may come from renewable sources that are virtually emission-free (excluding from the analysis the emissions embedded in the plant building process [22]). In the case of Italy, the average emission factor for electricity production would then drop to about 525 g/kWh_e, according to estimates drawn from [23]. With this emission factor, double-effect chillers would be competitive only for COP^{CEC} below about 3.1, while triple effect GACs or EDCs would be emission-efficient for COP^{CEC} values below about 4.2. Direct-fired single-effect chillers could be effective only for relatively high values of μ^W and relatively low values of COP^{CEC}. This confirms that single-effect absorption chillers should be mostly applied for waste heat recovery applications, where they can provide effective emission reduction in a number of cases [16,17].

4.3 CO_2 emission break-even results for average values in different countries

For a further general comparison between DFCs and CECs, Table 1 reports the maximum COP^{CEC} values for which, in correspondence of the overall electricity-related emission factors in some countries, adoption of typical double-effect and triple-effect GACs or EDCs would bring emission saving with respect to the CEC. Emission intensity data, assessed in terms of *average* values for overall power systems (including renewable sources), refers to 2007 for the UK [24] and to 2003 for the other countries [25].

Table 1. Maximum COP^{CEC} for positive CO_2 emission reduction from GACs and EDCs in different power systems

Country	μ^W [g/kWh_e]	double-effect GAC (*COP*=1.2)	triple-effect GAC or EDC (*COP*=1.6)
Norway	3	0.02	0.02
France	78	0.47	0.62
EU15	362	2.17	2.90
Japan	389	2.33	3.11
UK	430	2.58	3.44
Italy	525	3.15	4.20
USA	610	3.66	4.88

From Table 1, DFCs could boast emission reduction potential in countries such as Italy or USA, with relatively “polluting” power systems, mostly based on thermal power plants. However, only triple-effect GACs and EDCs could be competitive in countries such as Japan or aggregation such as the 15 European Union Countries at the year 2003 (EU15). Finally, in power systems based upon renewable sources (Norway) or nuclear energy (France), with very low CO_2 specific emissions per kWh_e, basically DFCs could play no role to bring CO_2 emission reduction.

4.4 Energy saving and CO_2 emission reduction analyses in different generation environments

For a broader picture of the potential of different cooling alternatives within a given generation framework, it is possible to perform parametric analyses on the entries of (11) and (16). Fig. 5 shows the *CPES* indicator (11) against the average electrical efficiency, with a DFC (with *COP* = 1.2, for instance a double-effect GAC), and with different values of the reference COP^{CEC}. In this case, DFCs can bring energy saving for relatively lower COP^{CEC} and η_e values. For instance, considering COP^{CEC} equal to 2, that is, for small residential chillers or air-conditioners and/or operating under severe outdoor conditions (warm climate), for η_e equal to 0.4 (around the average energy efficiency in Italy) energy saving of about 40% can be reached. However, for the same efficiency value and for high values of COP^{CEC} (for instance equal to 6, corresponding to large high-efficiency chillers), the energy saving is highly negative (the vertical axis in Fig. 5 and in the successive ones is cut at -100% for the sake of clarity). With the considered performance characteristics, this corresponds to a consistent increment of the primary energy needed for generating a certain amount of cooling power if adopting DFCs rather than CECs. The same reasoning can be applied to the CO_2 emission reduction (Fig. 6). Considering average emissions in the USA (Table 1), emission reduction of almost 20% can be obtained with respect to CECs with *COP*=3. However, for lower-emission frameworks (for instance, Japan), emission reduction can be obtained only for low COP^{CEC} values.

Fig. 7 and Fig. 8 report the same kind of analyses considering a DFC with *COP*=1.6 (for instance, a triple-effect GAC or an EDC). Better energy and environmental performance can now be reached in various conditions, above all in those countries with relatively lower generation efficiency and higher average emissions.

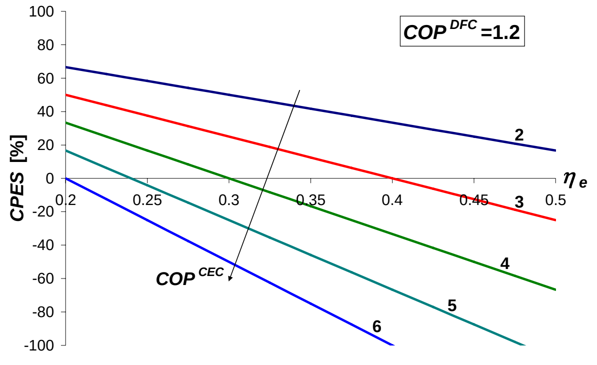

Fig. 5. Energy saving in different generation frameworks with COP^{DFC}=1.2.

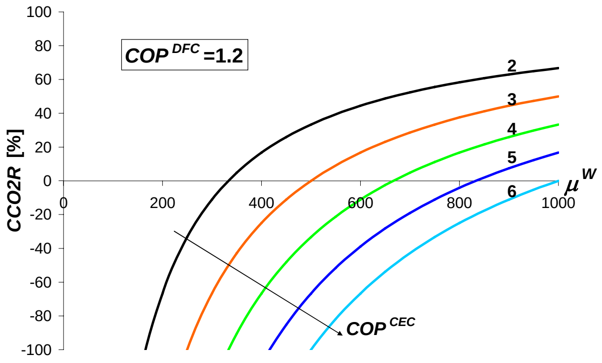

Fig. 6. CO_2 emission reduction in different generation frameworks with COP^{DFC}=1.2.

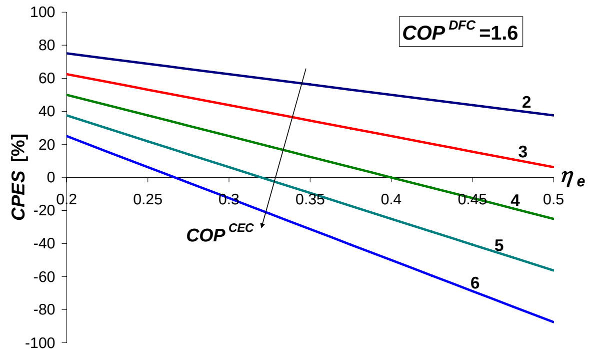

Fig. 7. Energy saving in different generation frameworks with COP^{DFC}=1.6.

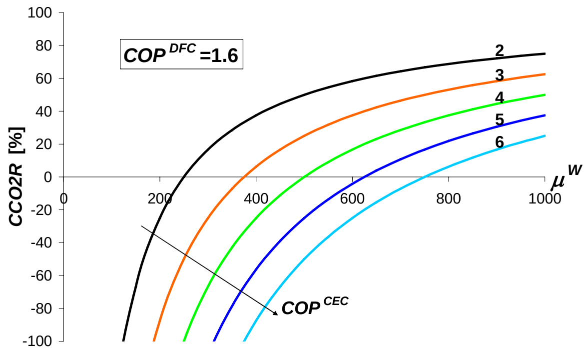

Fig. 8. CO_2 emission reduction in different generation frameworks with COP^{DFC}=1.6.

4.5 Marginal plant operation analysis

The analyses considered in Section 4.3 and Section 4.4 have mostly referred to average values for energy saving and emission reduction. However, above all for the environmental assessment, alternative approaches could be undertaken, as carried out in Section 3.1, for instance. In particular, as mentioned in the Introduction, it could be argued that DFCs are likely to displace CECs when peak electricity is generated, as it occurs in the central hours of summertime days, when air conditioners are fully operated. Indeed, air conditioning operation occurs at peak hours in several countries. On this assumption, the approach c) described in Section 3.5 appears the most appropriate. For instance, in the UK the CO_2 emission intensity from *marginal* plants is estimated to be equal to 570 g/kWh$_e$ [24]. According to this figure, the potential environmental performance of DFCs improves consistently with respect to considering the average value of 430 g/kWh$_e$ reported in Table I. For instance, with reference to distributed residential CECs with COP^{CEC} = 2.5, single effect absorption chillers could bring emission reduction of about 25% (Fig. 6), while for triple-effect or engine-driven chillers the *CCO2ER* could be as high as 45% (Fig. 8). Instead, if the analyses were based on average emission values, the emission reduction would be only marginally positive or about 25%, for double-effect and triple-effect (or engine-driven) chillers, respectively.

4.6 Further comments on the numerical applications

On the basis of the results of the analyses shown above, it can be clearly understood how the assessment of the environmental benefits from deploying a technology rather than another contains subjective components that might be related to the purpose of the study as well as to political strategies. For instance, in the future the emission trading scheme envisioned in several European countries signing the Kyoto's Protocol could be extended to include *any* type of generation technologies on every scale of application. In this case, not accounting for the dynamics of power system operation could lead to wrong environmental assessments [26], as well as send biased economic signals to the market [27]. Hence, policy action in this respect should be carefully planned.

Provided that the marginal plant operation is accounted for, the presence of competitive energy markets might render the environmental assessment extremely uncertain. Indeed, on the one hand nuclear and hydro sources are mostly operated with flat profiles, to cover the base load demand, so that the load-following operation is left to other, more polluting, plant typologies. This aspect would support the argument of DFCs displacing CECs in combination with marginal plants, and the fact that an *operational* dynamic assessment is sought. On the other hand, to establish indicative figures for marginal emission intensities might be a daunting task, since fast-changing energy market scenarios would boost the utilization of different sources, case by case. For instance, while low-efficiency and high-emission coal plants are claimed to be soon phased out in most countries, their utilization has lately risen consistently due to high gas prices that might make them more convenient with respect to modern high-efficiency gas combined cycles.

5 Concluding remarks and future works

In this paper, the two main typologies of chillers available on the market, namely, CECs and DFCs, have been compared from the energy and CO_2 emission standpoints. The comparison has been carried out by means of a comprehensive and unified approach based upon black-box energy and emission models, resulting in a unified structure of two novel indicators, the *CPES* and the *CCO2ER*. These indicators have been exploited for carrying out several types of assessments. In particular, break-even analyses have highlighted relevant numerical aspects of the energy and environmental performance of various cooling generation solutions within different power system frameworks. As a general result, double-effect GACs can be environmentally competitive above all in those countries where the power system is characterized by a high share of thermal generation units fuelled by coal or oil, with also relatively low average conversion efficiency. In addition, the development of high-efficiency triple-effect chillers, as well as EDCs, represent a promising alternative for both primary energy saving and CO_2 emission reduction. This could occur particularly for cases with average power system emissions higher than $\mu^W \cong 500 \div 600$ g/kWh$_e$ (for instance, Italy and USA) for typical values of COP^{CEC}.

However, as illustrated through numerical applications and widely discussed in the paper, different approaches other than those based on comparisons with average figures could and should be taken up. In particular, the electricity potentially displaced by adopting DFCs as opposed to CECs is arguably likely to be produced by *marginal* power plants operating in the power systems for peak and load-following applications. Being the emissions from peak power plants significantly higher than the average, the potential emission reduction from gas-fired chillers could be much higher than deemed. Such analyses could be quite complicated and should be supported by adequate measurement and information frameworks and framed within clear policy actions. Nevertheless, these analyses seem necessary in order to boost the most environmental-effective technologies.

Besides being energetically and environmentally effective, sustainable cooling generation technologies should be also economical. The economic analysis of DFCs and CECs is primarily related to market prices of electricity and natural gas, as well as to specific economic frameworks. For instance, the presence of high electricity rates in summertime peak hours could be an incentive to install potentially cheaper DFCs. However, a general comparison is not straightforward. In this respect, works in progress are aimed at extending the black-box approach introduced here to the economic assessment, so as to formulate a holistic approach for energy, environmental and economic assessment of different cooling alternatives within various energy and market frameworks.

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