Renewable and Sustainable Energy Reviews 82 (2018) 1497–1513

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables

Miguel Angel Gonzalez-Salazar[a,*], Trevor Kirsten[a], Lubos Prchlik[b]

[a] Disruptive Energy Lab, GE Global Research, Garching b. München, Germany
[b] Doosan Škoda Power, Plzen, Czech Republic

ARTICLE INFO

Keywords:
Gas turbines
Combined cycle
Aero-derivative
Coal power plants
Steam turbine
Conventional power generation
Flexibility
Back-up renewables
NOx
SOx
Carbon monoxide
Carbon dioxide
Emissions

ABSTRACT

This paper reviews the operational flexibility and emissions of gas- and coal-fired power plants today and in the future with higher renewables. Six study cases were considered: heavy duty gas turbines in simple and combined cycle, aero-derivative gas turbines, large-scale supercritical coal power plants and small- and mid-scale subcritical coal power plants. The most critical operational processes and pollutants associated with these plants were identified. Then, data was collected mainly from manufacturers, but also from academic research and grey literature. The data was compared and analyzed. Detailed comparisons of the power plant characteristics as well as the current and future flexibility and emissions are provided. Furthermore, a method to quantify the ability of conventional power plants to back-up renewables and the expected benefits from improved flexibility is proposed and evaluated. Results show that gas-fired power plants are not only more efficient, but also faster and generally less polluting than coal-fired power plants. However, at their respective minimum complaint load, gas plants are less flexible and produced more NOx and CO emissions than coal-fired power plants. Results also show that on average, an improvement of approximately 50% to 100% on power ramp rates, minimum power load, number of major power cycles and emissions for these plants is sought in the future to complement renewables.

1. Introduction

A clean, secure and efficient energy system is a prerequisite for modern societies. The concept of a low carbon economy has is origin in the United Nations Framework Convention on Climate Change (UNFCCC) adopted in Rio in 1992. Since then, developing a sustainably low-carbon economy has become the priority for many regions in the world. One region particularly active in the development of strategies and plans to achieve a low-carbon energy system and a low-carbon economy is the European Union (EU). The EU through its EU Energy Roadmap 2050 targets to supply 35% of electricity from renewable sources by 2020 and almost 100% by 2050 [1]. To achieve this, the EU Energy Roadmap 2050 foresees a massive deployment of renewable energy sources (mostly wind and solar) combined with smart grids and sustainable economic activities (housing, transport, industry, etc.). The EU is not alone in this effort as other regions are seriously deploying renewables and low carbon energy technologies (e.g. China, U.S., Japan, Brazil, etc.) [2].

Nonetheless, today fossil fuels dominate the global energy demand and this is likely to continue in the short- and mid-term. IEA projections show that renewable energy is will continue to grow rapidly from a small base, see Fig. 1. Furthermore, conventional power generation remains dominant at 74% in 2040 even under the New Policy Scenario. In 2040, under the new policy scenario, bioenergy, nuclear, other renewables and hydro are expected to be 11%, 7%, 6% and 3%, respectively [3]. In 2040, oil, gas and coal are expected to be 27%, 24% and 23% respectively [3]. Coal's share in primary energy demand is expected to be flat (0.2% growth), with declines in the EU (3.7%) and China (0.5%), while there is growth in India (3.6%) and South East Asia (4.4%) [3]. The changes in energy mix will be region dependent, for example affordable gas is expected to continue to replace coal in the US. Coal will remain in place, in the short-term, where gas is more expensive than coal, such as EU, India, and China. Coal demand is impacted by industrial consumption which is a large consumer of coal (40%). The global coal plants are expected to have a 3%-point efficiency increase [3]. This is achieved through technology

Abbreviations: Aero-GT, aero-derivative gas turbine; CC, combined cycle; CW, cooling water; EU, European Union; FGD, flue gas desulfurization; FL, full load; FSNL, full speed no load; GT, gas turbine; HDGT, heavy duty gas turbine; HL, house load; HP, high pressure; HRSG, heat recovery steam generator; IP, intermediate pressure; LHV, lower heating value; LP, low pressure; MCL, minimum compliant load; NSNL, no speed no load; OEM, original equipment manufacturer; SC, simple cycle; SOA, state of the art; ST, steam turbine

* Corresponding author.
E-mail addresses: gonzalez@ge.com, gnzmln@unife.it (M.A. Gonzalez-Salazar).

http://dx.doi.org/10.1016/j.rser.2017.05.278

Available online 14 July 2017

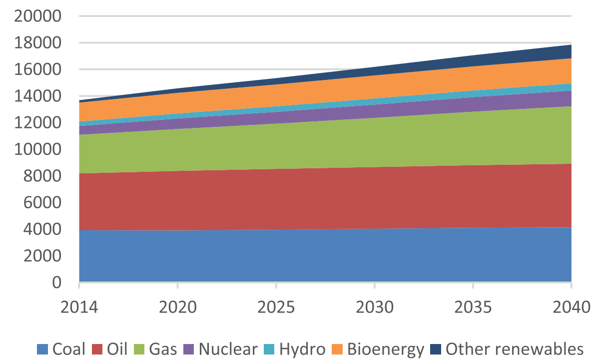

Fig. 1. World primary energy demand by fuel and scenario in the New Policies Scenario (Mtoe) [3].

improvements in the plants and the decommissioning of old plants. There is unlikely to be a direct exchange between technologies, for example replacing gas and coal fired plants with bioenergy plants. A more natural process is expected where bioenergy and other renewable plants will grow based on local regulations and market conditions. For example, photovoltaic solar is already the cheapest source of energy in some areas [4]. In summary, conventional power will be included in the mix for years to come and its contribution to enable renewable growth needs to be optimized.

While the benefits of a low-carbon energy system are multiple (i.e. lower emissions and environmental impact, energy independence, job creation, etc.), it also involves various challenges particularly to conventional power generation technologies. Renewable energy sources, mainly solar and wind power, are characterized by being not dispatchable. This implies that the power can't be dispatched, or supplied, on demand as is the case with conventional power, biomass and hydro. Renewables are among the most capital-intensive and lowest cost to operate. Once built, the least-cost approach is to run them as much as possible [5]. As electricity supply and demand must always balance, electricity systems require technologies that can respond to changes in power generation from renewables [2]. In the absence of commercially-available and cost-effective large scale energy storage capabilities, the effect of increasing penetration of solar and wind in some countries has been to force fossil-fired power plants (gas and coal) to deliver highly varying output to meet load at every instant [2,5–8].

Therefore, fossil-fueled power plants, originally designed to be base loaded, will increasingly need to operate on a load following or cyclic basis [8]. This means they need to cycle on and off and ramp up and down to part load more frequently, more rapidly and more cost-effectively [9]. However, increased cycling, load following and ramping may have various negative impacts on fossil-fuel power plants. Firstly, it can lead to fatigue and creep on components, which may result in higher capital and operational costs, increased forced outage rates and reduced lifetime [9]. Secondly, cycling and ramping results in degraded performance and higher emissions (viz. CO_2, NO_x, SO_2) over time [9]. These challenges are already impacting the operation of fossil-fueled power plants in many countries. In Germany, for example, to favor the deployment of renewables, there is an obligation to dispatch wind and solar ahead of other technologies. Consequently, highly efficient fossil-fueled power plants have been underutilized, often unprofitable, or even decommissioned despite their state of the art characteristics [7,10]. With an increasing penetration of renewables, these challenges are only expected to increase in the future.

Various alternatives to address the challenge of ensuring a more flexible electricity system, with growing renewables, have been explored. These include demand response, energy storage and flexible generation [2,5–8]. Demand response relates to the reduction or increase in the load to adapt to changes in supply. Techniques already deployed, or in development, include sophisticated forecasting of renewables and intelligent smart grids to best match electricity demand and supply [2]. Energy storage relates to the accumulation of electricity produced from renewables at one time for use later. While various energy storage technologies have been proposed with a varying degree of maturity, capacity and discharge duration [11], today there is a lack of a commercially-available and cost-effective large scale energy storage technology. Storage offers the potential to solve the problem of electricity production at the wrong time (temporal imbalance). The two main characteristics of storage technology are discharge time and capacity. Specific storage technologies can solve specific problems and there is no "one size fits all" solution. The installed storage capacity is 140 GW with 99% being hydro but this is small (2%) compared to the world installed 6000 GW [3,4]. Even though hydro is the dominant storage in place it can only be applied where there is suitable geography and available water, limiting growth within Europe. In the future, cheaper batteries are expected to offer new solutions in this storage domain [12]. Generation flexibility refers to the extent to which power technologies can respond to the variability in the residual load on different timescales [2]. Operators have typically relied on conventional power plants (e.g. gas- and coal-fired power plants) to balance demand and supply. With a higher share of renewables, these plants need not only to be able to react in a more flexible manner but also to do it in a profitable way. Flexibility of conventional power plants can be accomplished by improving and redesigning components, defining new operational strategies and identifying new market mechanisms [7]. Generation flexibility is expected to remain the most critical solution to deliver flexibility in the short- to medium-term, as it is more mature and less limited in capacity and geography than demand response and storage [2]. Moreover, it is expected that improving the flexibility characteristics of gas- and coal-fired power plants will contribute to the successful transition to low-carbon electricity systems.

On top of this, a location mismatch between power generation and consumption exist. To solve this issue, electrical transmission grids have been built. The European grid grew over time from regional independent grids to connected grids [13]. The distribution of power is done by the transmission system operators (TSO). The grid is operated by the European Network of Transmissions System Operators for Electricity (ENTSO-E) and comprises 307,000 km with an installed power generation capacity of 1024 GW [14]. The actual grid infrastructure doesn't meet future requirements. Rebuilding the grid infrastructure takes a very long time, is cost intensive ($746–$3318/MW/km) [15] and very often faces resistance from the local population. The costs for re-dispatch (network charge) is rising from year to year compared to energy charges [3]. In summary, the grid will contribute to renewable deployment but is not expected to solve the challenges fully.

There are various studies analyzing the flexibility characteristics of gas- and coal-fired power plants. Most of the existing studies focused on only one of the following topics: 1) separately analyzing the flexibility characteristics of either coal- [6,16–18] or gas-fired power plants [19–21] or 2) comparing the flexibility characteristics of some operational processes for these two technologies with a somewhat limited depth [2,7–10,22]. A few papers have investigated these two topics and further analyzed the ability of conventional power generation to backup growing renewables [23–26]. This paper aims at complementing these studies by offering a more detailed and rigorous analysis of the flexibility of multiple operational processes and associated emissions of coal- and gas-fired power plants today and in a future with growing renewables. The goals of this paper are: 1) identify representative design and operational conditions of typical gas- and coal-fired power plants, 2) review literature on current and possible future flexibility characteristics and emissions of those technologies and 3) propose a method to quantify the ability of conventional power plants to back-up renewables and the expected benefits from improved flexibility. The option of combining gas- and coal-fired power plants with carbon capture as a backup to renewables in a carbon constrained world is a long-term technology that was not considered. Instead, the paper focuses on the flexibility and emissions of conventional power generation without carbon capture as a short- to medium-term solution before a cost-effective energy storage solution is available. This analysis is expected to offer important insights to guide research and assess technology improvements as well as to provide inputs for long-term energy models assessing future energy systems.

This paper is structured as follows. Section 2 presents a general comparison of the characteristics of various power generation technologies. Section 3 describes the approach used to review and analyze published data. Section 4 presents a framework to evaluate the flexibility characteristics and emissions of gas and steam power plants. Section 5 presents design and operational details of representative examples of gas and steam turbines extracted from literature. Section 6 compares and discusses the flexibility characteristics and emissions of the different technologies. Section 7 shows a proposed method to quantify the ability of conventional power plants to back-up renewables and the expected benefits from improved flexibility. Finally, Section 8 discusses the most significant results of the investigation and presents conclusions.

2. Technology comparison

Table 1 shows the generally accepted pros and cons of the various power generation technologies. The focus is placed on the objective of this study, which is flexible fossil to complement variable renewable. Flexible generation technologies are currently the dominant source of system flexibility in virtually all power systems. The flexibility required is estimated at 10% of the installed renewable capacity [4,13].

Table 2 shows an assessment of technologies relative to the grid requirements [27]. The flexibility levels are summarized here:

- *Inflexible generation* technologies include inflexible nuclear, lignite and coal power plants, certain steam turbines with oil/gas as boiler fuel, and to a certain degree also gas turbine combined cycle plants, if designed accordingly. Also, most geothermal plants belong in this category. Inflexible power plants are designed for baseload operation, while start-up and ramping operations are rare and time-consuming. The constraint of thermal stresses in the thick-walled machinery of those plants operating at high pressures limits flexibility.
- *Flexible generation* technologies comprise flexible gas turbine combined cycle, flexible coal, biomass, biogas and concentrated solar (CSP). These power stations are designed to operate as mid-merit plants that can adjust their generation level to cope with load variations and start at short notice.
- *Highly flexible* power plants such as reservoir hydro, combustion engines or aero-derivative gas turbines, a sub-set of simple cycle gas turbines form the most flexible category. The additional cost of operating these plants more flexibly can be very low.

Table 1
Characteristics of power generation technologies.

Technologies	Pros	Cons
Oil	• High energy density • Best for mobile power applications	• Fossil fuel • Not preferred for power generation
Coal	• Cheapest energy source in certain regions	• Fossil fuel • Low efficiency and high emissions • Baseload power
Gas	• Economics significantly improved with unconventional gas	• Fossil fuel • Cleaner than coal • More flexible power
Nuclear	• No emissions	• Public safety concerns • Base load power • Disposal of hazardous waste
Hydro	• Renewable • Can be dispatchable	• Requires suitable geography and permitting • Negative environmental impact in reservoirs and rivers
Bioenergy	• Renewable • Can be dispatchable	• May compete with other land uses
Wind	• Renewable • Competitive on-shore economics	• Limited regional application • Public concerns, e.g. noise
Solar	• Renewable • Expected to be the cheapest power source in the future	• Limited regional application

Table 2
Flexibility characteristics of various power generation technologies.

Technology	Minimum load (% full load)	Ramping rate (% full load/ min)	Hot start-up time (h)
Hydro reservoir	5	15	0,1
Simple cycle gas turbine	15	20	0,16
Geothermal	15	5	1,5
Gas turbine combined cycle	20	8	2
Concentrated solar power	25	6	2,5
Steam plants (gas, oil)	30	7	3
Coal power	30	6	3
Bioenergy	50	8	3
Lignite	50	4	6
Nuclear	50	2	24

Refs.: [2,22,28].

3. Method

The approach used in this study, to review and analyze published information on flexibility and emissions of gas and steam turbines, is shown in Fig. 2. The IEA's definition of flexibility is adopted: "flexibility describes the extent to which an electricity system can adapt the pattern of electricity generation and consumption in order to balance supply and demand" [2]. In a first step, a framework and key processes describing the operational flexibility of thermal power plants is proposed. In a second step, representative examples of gas and steam turbines are defined for evaluation. In a third step, data from main original equipment manufacturers (OEM) of gas and steam turbines regarding design, emissions and the defined key flexibility processes are collected. In cases where data from OEM was not readily available, information was either collected from other sources including technical reports and scientific papers or generated through simulation models. In a fifth step, collected data is processed and average, minimum and maximum values of the key flexibility processes and emissions are presented and compared for the different examples of gas and steam turbines. Finally, a method to quantify the ability of conventional power plants to back-up renewables and the expected benefits from improved flexibility is proposed and a Monte Carlo is built for that purpose.

4. Approach

A framework to evaluate the flexibility and emissions of gas and steam power plants is proposed (see Fig. 3). This framework is derived from previous studies addressing the same challenge [2,6,7,16,28]. The proposed framework consists of eight of the most important opera-

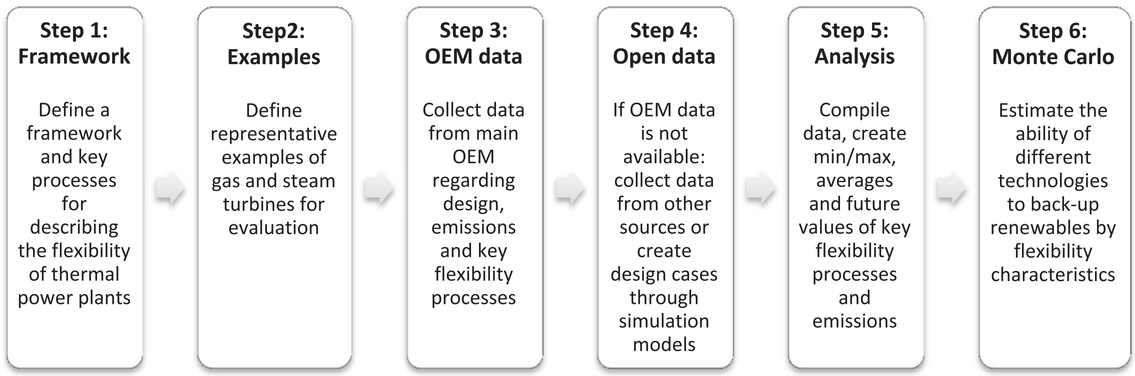

Fig. 2. Method for data analysis.

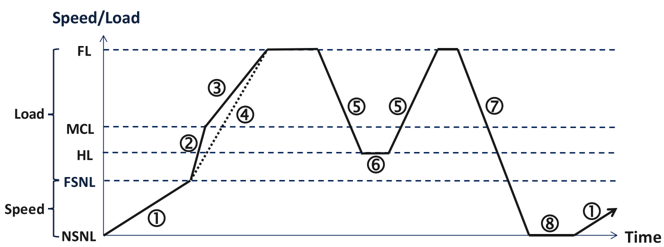

Fig. 3. Framework to evaluate the flexibility of gas and steam turbine power plants.

tional processes that describe the variation in speed and load of gas and steam power plants over time. A description of these processes is presented in Table 3.

It is important to note that processes 1–4 are dependent on the type of start-up, which can be hot, warm and cold starts. They refer to the shutdown period before the start and vary between manufacturers [29]. While there is no general agreement regarding how to define hot, warm and cold starts, in this study the following definitions are used:

- Hot start: < 8 h since plant shutdown
- Warm start: between 8 and 48 h since plant shutdown
- Cold start: > 48 h since plant shutdown

Regarding emissions, four pollutants are considered relevant for gas- and coal-power plants. These pollutants include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx) and sulfur oxides (SOx). While other pollutants may be produced in gas- and coal-fired power plants (e.g. heavy metals, volatile organic compounds, methane, ammonia, etc.), they are considered less important and out of the scope of this investigation. The emission of the considered pollutants is estimated as specific emission factors per megawatt-hour (kg/MWh) at full load and minimum complaint load (MCL) and as specific emissions factors per megawatt (kg/MW) during cold and hot starts.

5. Representative examples of gas and steam turbines

Six case studies that are representative examples of gas and steam turbines are included in this study (see Fig. 4).

Evaluation of gas turbine power plants focuses on two types, namely F-class heavy duty gas turbines (HDGT) and aero-derivative gas turbines. These two types of turbines have been selected because they are the largest installed fleet in the world on large-scale (> 200 MW) and small-scale (50 MW), respectively [30]. The F-class HDGT is analyzed both in natural gas-fired simple and combined cycles, while aero-derivative gas turbines are studied only in simple cycle. On the other hand, evaluation of steam turbine power plants focuses on two types as well, namely sub-critical and super-critical power plants. These two types of technologies cover a very large spectrum of steam turbines for power plant applications. Within the category of sub-critical cycle, two sub-cases are considered depending on the size. These include a small-scale power plant below 50 MW and a mid-size power plant with a rated power of about 300 MW. Within the category of super-critical cycle, the analyzed case is a large-scale coal-fired power plant with a rated power of 500 MW. Values about the design and key flexibility processes are collected from literature for each of these cases and are presented in the following sections.

5.1. Gas turbine power plants

5.1.1. Heavy duty gas turbines

Frame-F heavy duty gas turbines are today the largest installed fleet of gas turbines in the world [30]. While their capacity is expected to

Table 3
Processes describing the flexibility of gas and steam power plants.

Process number	Name	Description
1	No speed no load (NSNL) to full speed no load (FSNL)	It is the process of increasing the speed of the turbine from zero to the value at which the generator is synchronized to the grid frequency. At full speed the turbine can start generating power.
2	FSNL to minimum complaint load (MCL)	This is the process of increasing the load at full speed from zero to the MCL. MCL is the minimum load at which the turbine is complaint either with emissions or other restrictions.
3	MCL to full load (FL)	This is the process of increasing further the load from the MCL to full load.
4	FSNL to FL	This is the process of increasing the load from zero to 100%. Data regarding this process is typically more readily available than data regarding processes 2) and 3).
5	Ramp rate up and down	These are the processes of rapidly increasing or reducing the load of the turbines between a minimum represented by the house load (HL) and a maximum represented by the full load.
6	House load (HL)	House load is the capacity generation at which the own consumption of the power plant is covered and no surplus is exported to the grid.
7	Shutdown	It is the process of reducing the load and speed of the turbine from full load to zero, practically ceasing operation.
8	Minimum downtime	It is the minimum period that a power plant should be out of operation. It does not represent a hard-physical limit, but rather an economic limit since operators are interested in minimizing the number or start-ups and shut-downs to reduce excessive thermal stress on power plant equipment [22]

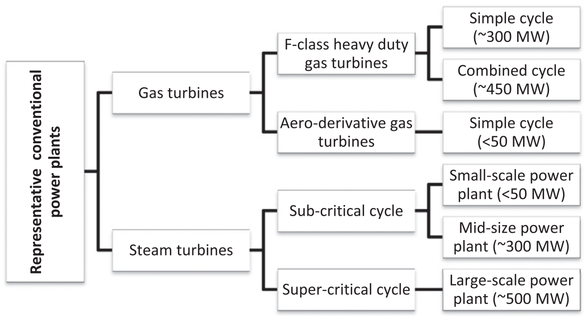

Fig. 4. Representative examples of gas and steam turbine power plants.

Table 4
Design characteristics of F-class HDGT in simple cycle.

Characteristic	Minimum	Maximum	Average
Pressure ratio	16.8	20	18.4
Turbine inlet temperature (°C)	1288	1399	1343
Exhaust temperature (°C)	576	641	598
Air mass flow (kg/s)	654	736	690
Net power generated (MWe)	269	334	301
LHV Heat Rate (kJ/kWh)	8880	9458	9161
Net LHV efficiency (%)	38.1	40.5	39.3

Notes:
[1]Refs.: [33,35–40].

Table 5
Design characteristics of F-class HDGT in combined cycle.

Characteristic[1]	Minimum	Maximum	Average
ST power generated (MW)	129	146	138
Combined cycle power (MW)	398	475	439
Combined cycle efficiency (%)	56.4	58.2	57.4
HRSG efficiency (%)	83.5	87.5	85.2
ST electrical efficiency (%)	29.2	31.3	30.1
Exhaust flow (kg/s)	657	745	697
HP pressure (bar)[2]	91.90	91.90	91.90
IP pressure (bar)[2]	11.41	11.41	11.41
LP pressure (bar)[2]	1.19	1.19	1.19
Condensing pressure (bar)[2]	0.059	0.059	0.059
HP steam temperature (°C)[2]	548	550	549
IP steam temperature (°C)[2]	264	266	265
LP steam temperature (°C)[2]	104	104	104
Overall steam flow (kg/s)	112	124	119
HRSG pressure drop (mbar)[2]	24	24	24
Duct & stack pressure drop (mbar)[2]	19	19	19
Stack temperature post HRSG (°C)	92	107	101

Notes:
[1] Ref.: [33].
[2] For simplicity, the steam conditions of the cycle, such as LP/IP/HP pressures and temperatures have been maintained unchanged for the different turbines.

grow due to their high reliability and availability, their growth between 2010 and 2015 has been lower than those of advanced gas turbines (i.e. G-, H- and J-class) [31]. Frame-F heavy duty gas turbines are characterized by having firing temperatures around 1300–1400 °C [32] and are typically in the 170–300 MW range. Representative design characteristics of Frame-F heavy duty gas turbines in simple and combined cycle are presented in Tables 4 and 5, respectively. For the simple cycle, characteristics of gas turbines are extracted from main OEM datasheets. In total, six machines are included in the analysis: AE94.3A (Ansaldo), M701F4 (Mitsubishi), 9F0.03 (GE), 9F0.04 (GE), 9F0.05 (GE) and SGT5-4000F (Siemens). While F-class gas turbines are, to a large degree, standardized, heat recovery steam generators (HRSG) and steam turbines in combined cycles are very heterogeneous. HRSGs and steam turbines are customized for each application and are therefore very site-specific or unique for every single project. For this reason, it is difficult to generalize design data on these components. In this study, a pragmatic approach is proposed. For each of the identified F-class gas turbines, a combined cycle model is built in the process simulation software GT Pro v25 [33]. The chosen configuration is a three-pressure HRSG, and a three-casing condensing reheat steam turbine (high-pressure, intermediate-pressure and low-pressure), which is the typical configuration for F-class HDGT combined cycle [34], see Fig. 5. Then, specific HRSG and steam turbine are designed for each of the identified F-class gas turbines and their characteristics are subsequently compared.

Representative values of key processes describing the operational flexibility of F-class HDGT are presented in Tables 6 and 7. For flexibility processes 1–4, current and expected future values are disaggregated by the type of start (i.e. hot, warm and cold) and type of thermodynamic cycle (i.e. simple and combined cycle) and are shown in Table 6. While information from OEM was available to a certain extent, for some processes it was necessary to collect information from other sources such as technical reports and scientific papers. For flexibility processes 5–8, current and expected future values are disaggregated by the type of cycle (i.e. simple and combined cycle) and are shown in Table 7. Current and future values of the specific emission factors for the F-class HDGT in simple and combined cycle are presented in Tables 13 and 14. Specific emission factors are presented at full load and minimum complaint load as well as cold and hot starts.

5.1.2. Aero-derivative gas turbines

Aero-derivative gas turbines (Aero-GT) are by far the largest global installed fleet at a small-scale, i.e. below ~ 50 MW [30]. Aero-derivative gas turbines consist of an aircraft-derivative gas generator and a free-power turbine. Aero-GTs are characterized by being lighter, more compact and multi-shaft, having faster installation times and lower operational and maintenance costs than heavy duty gas turbines [61]. Aero-GT are typically operated in simple cycles. While some Aero-GT are operated in combined cycles, they are not a representative case [30]. For this reason, in this study only Aero-GT in simple cycle is considered. As for the HDGT, characteristics of Aero-GT are extracted from main OEM datasheets. In total, 54 machines are included in the analysis (see Table 8). Representative values of key processes describing the operational flexibility of Aero-GT are presented in Table 9. Like HDGT in simple cycle, data on warm and cold starts for Aero-GT was found to be the same as that for hot starts. Thus, presented start values are representative for any type of start. Current and future values of the specific emission factors for the Aero-GT are presented at full load and minimum complaint load as well as cold and hot starts in Tables 13 and 14.

5.2. Coal power plants

Thermodynamic performance of pulverized coal-fired power plants is dependent on the steam conditions entering the steam turbine. The thermodynamic cycle can be subcritical, supercritical and ultra-supercritical depending on the steam conditions. Subcritical refers to pressures below the critical point of water (221 bar), while supercritical refers to pressures above it. Ultra-supercritical refers to pressures above 221 bar and temperatures above 590 °C [17]. The net efficiency of the power plant is strongly dependent on the steam conditions. The efficiency of subcritical plants ranges between 33% and 39%, it increases to 38–42% in supercritical plants and above 42% in ultra-supercritical plants [17]. Ultra-supercritical plants are superior in efficiency, however they are not representative of the total global installed capacity. In fact, subcritical and supercritical power plants account for more than 95% of the global capacity (~ 80% subcritical and ~ 15% supercritical) [71]. Since subcritical and supercritical coal-fired power plants are currently the most representative technologies, they are selected as study cases. For the selected cases, values about key flexibility processes are collected from the literature, while design

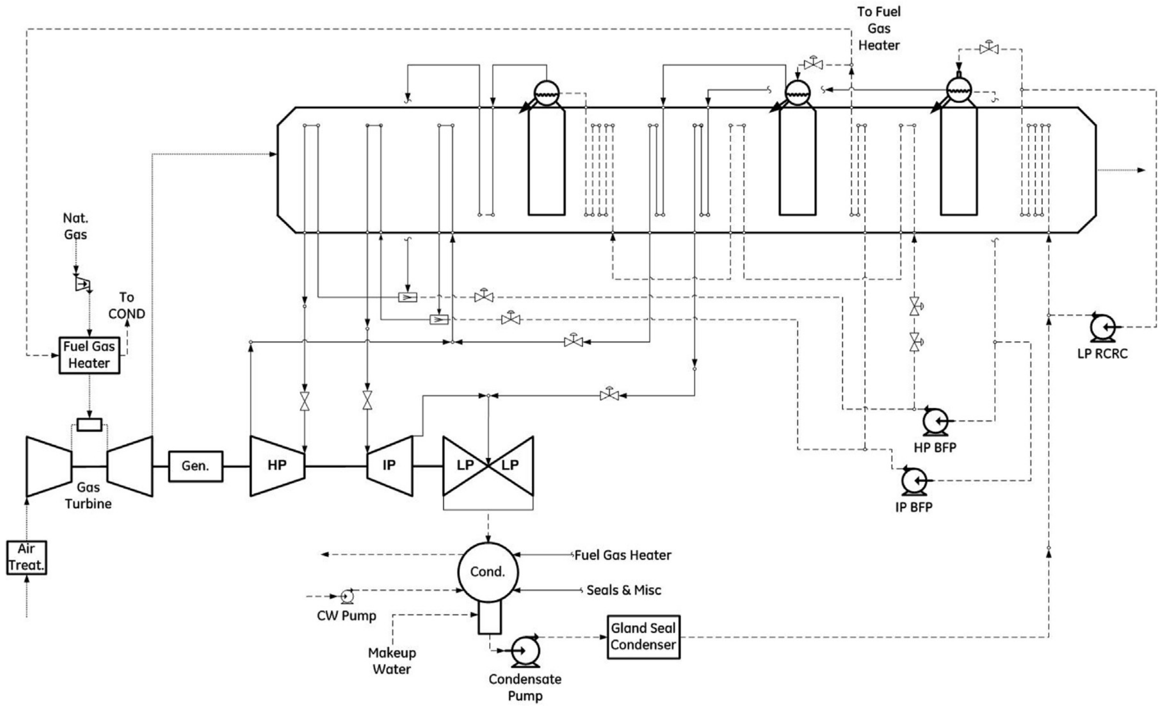

Fig. 5. Typical layout of a F-class HDGT combined cycle.

Table 6
Representative values of flexibility processes 1–4 in F-class HDGT.

Characteristic		Hot				Warm[1]				Cold[1]			
		Current values			Future values	Current values			Future values	current values			Future values
		Min	Max	Av.		Min	Max	Av.		Min	Max	Av.	
Number of starts (lifetime)		125	5000	2125	4250	100	900	515	N.A.	75	2500	746	N.A.
Start combined cycle (min)	NSNL to FSNL	4.0	14.0	8.5	N.A.	7	28.4	15.9	N.A.	6.2	28.8	15.1	N.A.
	FSNL to MCL	4.5	22.9	10.8	N.A.	N.A.	N.A.	36.3[2]	N.A.	N.A.	N.A.	63.0[2]	N.A.
	MCL to FL	7.8	25.0	20.0	N.A.	N.A.	N.A.	67.4[2]	N.A.	N.A.	N.A.	117.1[2]	N.A.
	FSNL to FL	27.2	39.5	30.7	N.A.	73.0	133.3	103.7	N.A.	138.3	240.0	180.1	N.A.
	NSNL to FL	32.0	45.0	39.3	24.6	95.0	144.0	119.6	75.2	145	255	195.2	122.8
Start combined cycle (MW/min)	NSNL to FSNL	0	0	0	0	0	0	0	0	0	0	0	0
	FSNL to MCL	9.5	42.2	26.7	N.A.	N.A.	N.A.	5.4	N.A.	N.A.	N.A.	3.1	N.A.
	MCL to FL	8.9	30.9	14.2	N.A.	N.A.	N.A.	3.6	N.A.	N.A.	N.A.	2.1	N.A.
	FSNL to FL	10.8	16.6	14.4	N.A.	3.0[3]	6.5[3]	4.2	N.A.	1.7[3]	3.4[3]	2.4	N.A.
	NSNL to FL	9.5	13.5	11.2	17.8	2.8[3]	5.0[3]	3.7	5.8	1.6[3]	3.3[3]	2.2	3.6
Start simple cycle (min)	NSNL to FSNL	4.0	14.0	8.5	N.A.	4.0[4]	14.0[4]	8.5[4]	N.A.	4.0[4]	14.0[4]	8.5[4]	N.A.
	FSNL to MCL	2.4	25.0	7.6	N.A.	2.4[4]	25.0[4]	7.6[4]	N.A.	2.4[4]	25.0[4]	7.6[4]	N.A.
	MCL to FL	3.6	8.0	6.5	N.A.	3.6[4]	8.0[4]	6.5[4]	N.A.	3.6[4]	8.0[4]	6.5[4]	N.A.
	FSNL to FL	6.0	30.7	14.1	N.A.	6.0[4]	30.7[4]	14.1[4]	N.A.	6.0[4]	30.7[4]	14.1[4]	N.A.
	NSNL to FL	10.0	44.7	22.6	11.7	10.0[4]	44.7[4]	22.6[4]	11.7	10.0[4]	44.7[4]	22.6[4]	11.7
Start simple cycle (MW/min)	NSNL to FSNL	0	0	0	0	0	0	0	0	0	0	0	0
	FSNL to MCL	5.3	51.2	25.3	N.A.	5.3[4]	51.2[4]	25.3[4]	N.A.	5.3[4]	51.2[4]	25.3[4]	N.A.
	MCL to FL	21.9	51.2	31.1	N.A.	21.9[4]	51.2[4]	31.1[4]	N.A.	21.9[4]	51.2[4]	31.1[4]	N.A.
	FSNL to FL	10.9	51.2	26.7	N.A.	10.9[4]	51.2[4]	26.7[4]	N.A.	10.9[4]	51.2[4]	26.7[4]	N.A.
	NSNL to FL	7.5	30.7	16.2	25.7	7.5[4]	30.7[4]	16.2[4]	25.7	7.5[4]	30.7[4]	16.2[4]	25.7

Notes:
[1] Data on warm and cold starts is generally not as available as data on hot starts.
[2] Data not available for warm and cold starts in public references. Estimated to be proportional to the data for hot start.
[3] Data not available for warm and cold starts in public references. Calculated by dividing the minimum/maximum combined cycle power shown in Table 5 by the maximum/minimum FSNL to FL and total starting times.
[4] Data on warm and cold starts for HDGT in simple cycle was found to be the same as that for hot starts. This suggests that start of gas turbines in simple cycles is not dependent on the downtime.

Table 7
Representative values of flexibility processes 5–8 in F-class HDGT.

Characteristic	Current values			Future values
	Minimum	Maximum	Average	
MCL simple cycle (% FL)	35.0	40.0	37.5	20.0
MCL simple cycle (MW)	94	133	113	60.2
MCL simple cycle efficiency (%)	23.4	29.8	26.8	N.A.
MCL combined cycle (% FL)	32.6	53.8	45.2	30.0
MCL combined cycle (MW)	139	241	198	132
MCL combined cycle efficiency (%)	49.1	55.4	51.8	N.A.
FL to MCL simple cycle (min)	3.7	8.2	7.0	4.1
FL to MCL combined cycle (min)	7.7	13.1	10.2	8.1
Ramp-rate simple cycle (MW/min)	22.3	50.0	29.1	58.2
Ramp-rate simple cycle (%FL/min)	7.5%	16.3%	9.6%	19.3%
Ramp-rate combined cycle (MW/min)	22.0	26.0	23.5	47.0
Ramp-rate combined cycle (%FL/min)	5.2%	6.0%	5.4%	10.8%
House load simple cycle (% FL)	1.6	1.9	1.7	N.A.
House load simple cycle (MW)	4	6	5	N.A.
House load combined cycle (% FL)	2.0	2.2	2.1	N.A.
House load combined cycle (MW)	8	10	9	N.A.
Turning down (min)	21.0	60.0	38.3	34.8
Turning down (MW/min)	7.9	19.0	11.5	12.6
Minimum downtime simple cycle (min)	0	360	113	N.A.
Minimum downtime combined cycle (min)	30	360	143	N.A.

Notes:
[1]Refs.: [10,33,35–38,41–60].

Table 8
Design characteristics of Aero-GT in simple cycle.

Characteristic	Minimum	Maximum	Average
Pressure ratio	14.8	34.1	23.9
Turbine inlet temperature (°C)[3]	1200	1200	1200
Exhaust gas temperature (°C)	431	530	485
Air mass flow (kg/s)	45	138	86
Net power generated (MW)	14	58	33
LHV Heat Rate (kJ/kWh)	8229	10,483	9476
Net LHV efficiency (%)	33.5	43.1	38.4

Notes:
[1]Gas turbines included, General Electric: LM1600 PD (LW & HW), LM1600 PE LW (C1 & C2), LM1600 PE HW (C1 & C2), LM1800e (LP, HP & DLE), LM2000 (C1, C2, C3 & DLE), LM2500 (DLE, SAC, +), LM6000 (PF, PF SPRINT, PG, PG SPRINT, PH, PH SPRINT, DLE & SAC), TM2500; Siemens: RB211-GT61 DLE, RB211-GT62 DLE, RB211-Gzero (RT-56, RT-62), RB211-H63 (DLE & WLE); Kawasaki: L30A; Solar Turbines: Titan 130, Titan 250.
[2]Refs.: [33,62–68].
[3]No specific details on this parameter are readily available, therefore 1200 °C was taken as a representative value for all turbines.

Table 9
Representative values of flexibility processes in Aero-GT.

Characteristic	Current values[1]			Future values
	Minimum	Maximum	Average	
MCL (% FL)	18.0	75.0	50.2	20.0
MCL (MW)	9	29	16	6.6
MCL efficiency (%)	31.7	40.8	36.4	N.A.
Ramp rate (MW/min)	30.0	50.0	39.0	77.9
Ramp rate (%FL/min)	82%	132%	97%	194%
FL to MCL (min)	0.4	1.2	0.6	0.3
NSNL to FSNL (min)	2.0	6.0	3.7	N.A.
FSNL to MCL (min)	1.0	4.0	2.3	N.A.
MCL to FL (min)	1.0	4.0	2.3	N.A.
FSNL to FL (min)	2.0	8.0	4.6	N.A.
NSNL to FL (min)	4.0	13.0	8.3	2.3
NSNL to FSNL (MW/min)	0	0	0	0
FSNL to MCL (MW/min)	5	47	18	N.A.
MCL to FL (MW/min)	5	47	18	N.A.
FSNL to FL (MW/min)	5	47	18	N.A.
NSNL to FL (MW/min)	3	28	9	14.4
House load (% FL)	1.4	2.9	2.1	N.A.
House load (MW)	0.3	1.6	0.7	N.A.
Turning down (min)	1	14	5.5	1.5
Turning down (MW/min)	2	30	20.2	22.2
Minimum downtime (min)	0	360	113	N.A.

Notes:
[1]Data on warm and cold starts for Aero-GT was found to be exactly the same as that for hot starts. This suggests that start of Aero-GT is not dependent on the downtime.
[2]Refs.: [10,21–29,33,69,70].

characteristics are taken from models built in the process simulation software Steam Pro v25 [33].

5.2.1. Subcritical cycle

Steam cycle operating parameters in subcritical coal-fired power plants are strongly dependent on size. In this study, two sizes are considered representative. The first case refers to a small-scale power plant with a rated power below 50 MW, which is representative of small-scale coal- and biomass-fired power plants. It is a non-reheat configuration, with a condensing single casing turbine, feedwater heaters and a once-through water cooled condenser (see Fig. 6). The second case refers to a mid-size power plant with a rated power of about 300 MW, which is representative of aging plants with more than 15 years of operation. This case is a single reheat configuration, with a condensing and multiple casing turbine (one high-pressure turbine, one intermediate-pressure turbine and one double flow low-pressure turbine), feedwater heaters, boiler-feed pump turbine and a once-through water cooled condenser (see Fig. 7). Representative design characteristics of these two subcritical power plants are shown in Table 10. Values about key flexibility processes are shown in Tables 11 and 12. On the other hand, current and future values of the specific emission factors are shown in Tables 13 and 14.

5.2.2. Supercritical cycle

In supercritical cycles, the steam pressure is above the critical point and the fluid is in a state where there is no distinction between liquid and gaseous phases. For this reason, there is no need to separate the water from the steam in a boiler drum as typically done in subcritical cycles. Instead, supercritical cycles use once-through boilers, which do not contain drums [17,18]. Supercritical technology is already used in

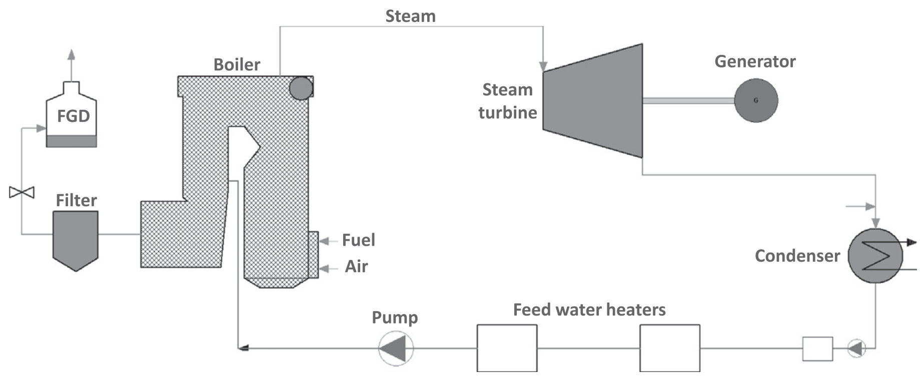

Fig. 6. Typical layout of a sub-critical coal power plant below 50 MW. Adapted from [33].

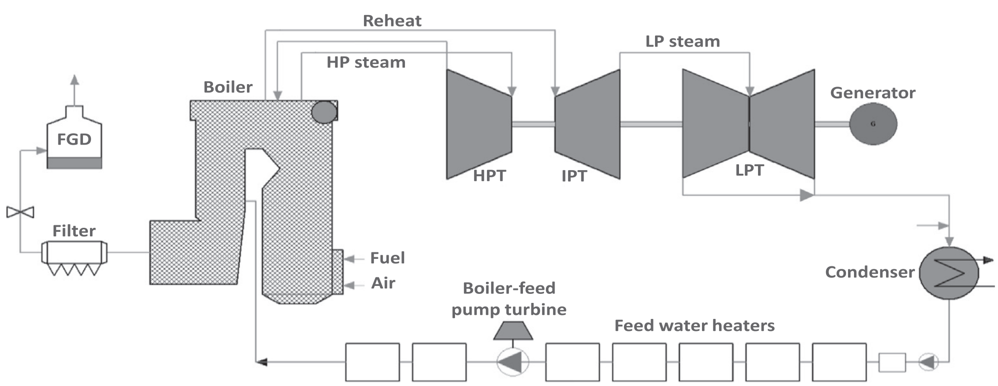

Fig. 7. Typical layout of a subcritical coal power plant ~ 300 MW. Adapted from [33].

about 18 countries and has become a 'minimum standard' in industrialized countries. It accounts for about 25% of the global installed fleet and is expected to grow [18]. While the first generation of supercritical plants was below 400 MW, currently units of up to 1 GW are being built [18]. However, the size of supercritical units varies substantially depending on the country [18]. For simplicity, in this study a supercritical coal-fired power plant with a rated power of 500 MW is considered representative. Representative design characteristics of this supercritical coal-fired power plant are shown in Table 10. Values about key flexibility processes are shown in Tables 11 and 12. On the other hand, current and future values of the specific emission factors are shown in Tables 13 and 14.

6. Analysis of results

Representative design and operational conditions as well as emissions of gas- and coal-fired power plants have been gathered from multiple sources and processed. A comparison of the power output and efficiency of the different power plants at full load and at the minimum complaint load (MCL) can be seen in Fig. 8. Gas turbines are found to be more efficient than coal power plants at full load and at minimum complaint load. However, their efficiency range is broader and their minimum power load is higher (except for the Aero-GT) than those of coal power plants.

A comparison of an average full operating cycle time[1] after hot and cold starts for all technologies is shown in Fig. 9. The technology with the fastest cycle time for hot and cold starts is the Aero-GT (45 min), followed by the heavy-duty gas turbine in simple cycle (90 min) and in combined cycle (120–280 min, respectively). Cycle times of coal power plants are significantly slower than gas turbines irrespective of size. At power outputs above 100 MW, the cycle times of coal power plants are 2.5–2.8 times higher than gas turbine combined cycles. At power outputs below 50 MW, the difference is more pronounced and cycle times are 7–17 times higher than Aero-GT.

A comparison of current vs future MCL, ramping, hot and cold start times for the different technologies is shown in Fig. 10. The lowest current MCL observed is about 10–20% of full load, which is offered by the Aero-GT and all the coal power plants. However, the range of MCL for these technologies is the broadest across all technologies, reaching in some cases up to 60–70% of the full load. In the future, MCL for Aero-GT and coal power plants is expected to remain in the lower end of this range, i.e. around 20% of the full load. Heavy duty gas turbines offer current MCL values around 40–50% of full load but with a narrower range than coal power plants. In the future, these values are expected to reduce to 20% for HDGT in simple cycle and to 30% in combined cycle.

Ramping rates are generally higher in gas turbines than in coal power plants. While in gas turbines they range between 25–50 MW/min (representing 5–100% of the full load per minute), in coal power plants they range between 2 and 40 MW/min (representing 0.5–8% of the full load per minute). Technologies with the fastest ramping rates include Aero-GT (80–100% full load per minute) and heavy duty gas turbines in simple cycle (8–15% full load per minute). For these technologies, ramping rates are expected to increase significantly in the future, i.e. 75 MW/min (200% full load per minute) is expected for Aero-GT and 50–60 MW/min for heavy duty gas turbines (20% full load per minute). For coal power plants, ramping rates are expected to moderately increase to 20 MW/min (5% full load per minute).

Coal power plants show significantly higher cold and hot start-up times than gas turbines. Start-up times in coal power plants range between 100–300 min in hot starts and 450–900 min in cold starts. In contrast, start-up times in gas turbines range between 4–45 min in hot starts and 4–250 min in cold starts. Technologies relying on heat transfer for power generation such as coal power plants and combined cycles are generally more affected by the shutdown time before the start

[1] It consists of all the operational processes described in Section 3. For simplicity, it is assumed that the time at full load and MCL is 10min for all technologies.

Table 10
Design characteristics of the different coal power plants.

Characteristic[1]	Subcritical (< 50 MW)[2]			Subcritical (300 MW)[3]			Supercritical (500 MW)[4]		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
HP pressure (bar)	57	89	71	146	182	164	305	305	305
HP temperature (°C)	452	513	483	543	544	543	602	602	602
IP pressure (bar)	–	–	–	35	41	38	71	71	71
IP temperature (°C)	–	–	–	542	542	542	621	621	621
LP pressure (bar)	–	–	–	7	7	7	7	7	7
LP temperature (°C)	–	–	–	306	323	314	298	298	298
Overall steam flow (kg/s)	24	55	40	170	299	235	323	481	402
Condensing pressure (mbar)	69	69	69	69	69	69	69	69	69
Exhaust gas (kg/s)	34	75	55	261	445	354	464	689	576
Adiabatic flame temperature (°C)[5]	1181	1204	1199	1204	1204	1204	1204	1204	1204
Fuel flow (kg/s)[6]	2.1	4.7	3.4	16.3	27.9	22.2	29.0	43.2	36.0
Boiler LHV efficiency (%)	91.7	92.2	91.8	92.2	92.2	92.2	92.2	92.6	92.5
Stack temperature (°C)	62.7	62.9	62.8	62.7	62.7	62.7	62.6	62.7	62.6
Net power generated (MW)	20	50	35	200	350	275	400	600	500
LHV Heat Rate (kJ/kWh)	10,854	12,200	11,567	9222	9463	9363	8330	8408	8353
LHV efficiency (%)	29.5	33.2	31.2	38.0	39.0	38.5	42.8	43.2	43.1

[1] All data extracted from Steam Pro v25 [33] using the 'design for low cost' criteria.
[2] Four sub-cases are considered in Steam Pro v25: 20 MW, 30 MW, 40 MW and 50 MW.
[3] Four sub-cases are considered in Steam Pro v25: 200 MW, 250 MW, 300 MW and 350 MW.
[4] Five sub-cases are considered in Steam Pro v25: 400 MW, 450 MW, 500 MW, 550 MW and 600 MW.
[5] It is the adiabatic flame temperature at the furnace in the boiler. Excess air is assumed to be 20%.
[6] Fuel used is Pennsylvania upper, a medium-volatile bituminous coal. LHV (moisture and ash included) = 32,184 kJ/kg. Proximate analysis (%W): moisture 2.1%, ash 6.1%, volatile matter 24.4%, fixed carbon 67.4%.

Table 11
Representative values of flexibility processes 1–4 in coal power plants.

Type of plant	Characteristic	Hot				Warm				Cold			
		Current values			Future values	Current values			Future values	Current values			Future values
		Min	Max	Av.		Min	Max	Av.		Min	Max	Av.	
Subcritical (< 50 MW)	Number of starts	N.A.	N.A.	5000	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	200	N.A.
	NSNL to FSNL (min)	60	90	75	N.A.	120	300	210	N.A.	360	420	390	N.A.
	FSNL to FL (min)[1]	70	210	138	N.A.	85	85	87	N.A.	78	480	254	N.A.
	NSNL to FL (min)	130	300	213	139	205	385	297	193	438	900	644	419
	NSNL to FSNL (MW/min)	0	0	0	0	0	0	0	0	0	0	0	0
	FSNL to FL (MW/min)[2]	N.A.	N.A.	0.25	N.A.	N.A.	N.A.	0.40	N.A.	N.A.	N.A.	0.14	N.A.
	NSNL to FL (MW/min)[3]	N.A.	N.A.	0.16	0.25	N.A.	N.A.	0.12	0.18	N.A.	N.A.	0.05	0.08
Subcritical (300 MW)[4]	Number of starts	N.A.	N.A.	5000	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	200	N.A.
	NSNL to FSNL (min)	60	90	75	N.A.	120	300	210	N.A.	360	420	390	N.A.
	FSNL to FL (min)[1]	70	210	138	N.A.	85	85	87	N.A.	78	480	254	N.A.
	NSNL to FL (min)	130	300	213	139	205	385	297	193	438	900	644	419
	NSNL to FSNL (MW/min)	0	0	0	0	0	0	0	0	0	0	0	0
	FSNL to FL (MW/min)[2]	N.A.	N.A.	1.99	N.A.	N.A.	N.A.	3.17	N.A.	N.A.	N.A.	1.08	0.00
	NSNL to FL (MW/min)[3]	N.A.	N.A.	1.29	1.98	N.A.	N.A.	0.93	1.43	N.A.	N.A.	0.43	0.66
Supercritical (500 MW)	Number of starts	N.A.	N.A.	5500	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	200	N.A.
	NSNL to FSNL (min)	60	90	75	N.A.	120	300	210	N.A.	360	420	390	N.A.
	FSNL to FL (min)[1]	30	210	103	N.A.	120	180	158	N.A.	78	300	177	N.A.
	NSNL to FL (min)	90	300	178	116	240	480	368	239	438	720	567	368
	NSNL to FSNL (MW/min)	0	0	0	0	0	0	0	0	0	0	0	0
	FSNL to FL (MW/min)[2]	N.A.	N.A.	4.84	N.A.	N.A.	N.A.	3.16	N.A.	N.A.	N.A.	2.83	N.A.
	NSNL to FL (MW/min)[3]	N.A.	N.A.	2.80	4.32	N.A.	N.A.	1.36	2.09	N.A.	N.A.	0.88	1.36

Notes:
[1]Calculated as (NSNL to FL) − (NSNL to FSNL).
[2]Calculated as (FSNL to FL) divided by the average rated power.
[3]Calculated as (NSNL to FL) divided by the average rated power.
[4]FSNL to MCL and MCL to FL processes were not readily available in literature for any of the types of coal power plant.
[5]Flexibility processes 1–4 measured in minutes for the subcritical power plants at 50 and 300 MW are the same.
[6]Refs.: [2,6–8,22,29,33,57,70,72].

Table 12
Representative values of flexibility processes 5–8 in coal power plants.

Characteristic	Subcritical (< 50 MW)				Subcritical (300 MW)				Supercritical (500 MW)			
	Current values			Future values	Current values			Future values	Current values			Future values
	Minimum	Maximum	Average		Minimum	Maximum	Average		Minimum	Maximum	Average	
MCL (% FL)	10.0	60.0	40.9	20.0	10.0	60.0	40.9	20.0	20.0	50.0	37.0	20.0
MCL (MW)	3.5[1]	21.0[1]	14.3[1]	7.0	27.5[1]	165.0[1]	112.5[1]	55.0	100.0[1]	250.1[1]	185.1[1]	100.0
MCL efficiency (%)	25.2[2]	28.2[2]	26.7[2]	N.A.	32.5[2]	35.5[2]	34.0[2]	N.A.	37.1[2]	40.1[2]	38.6[2]	N.A.
FL to MCL (min)	5.0[3]	155.2[3]	19.9[3]	16.1	5.0[3]	155.2[3]	19.9[3]	16.1	6.3[3]	121.2[3]	18.0[3]	29.2
Ramp-rate (MW/min)	0.2[4]	2.8[4]	1.0[4]	1.7	1.6[4]	22.0[4]	8.2[4]	13.7	3.3[4]	40.0[4]	17.5[4]	29.9
Ramp-rate (%FL/min)	0.6%	8.0%	3.0%	5.0%	0.6%	8.0%	3.0%	5.0%	0.6%	8.0%	3.07%	5.0%
House load (MW)[5]	1.4	3.4	2.4	N.A.	13.5	26.4	19.9	N.A.	17.2	25.7	21.5	N.A.
House load (% FL)[6]	6.8	7.0	6.9	N.A.	6.7	7.6	7.2	N.A.	4.3	4.3	4.3	N.A.
Turning down (min)[7]	33.0	86.0	53.8	23.0	33.0	86.0	53.8	23.0	33.0	86.0	53.8	41.9
Turning down (MW/min)[8]	0.4	1.1	0.7	1.5	3.2	8.3	5.1	11.9	15.2	5.8	9.3	11.9
Minimum downtime (min)	120	900	360	N.A.	120	900	360	N.A.	240	240	240	N.A.

[1] Calculated by multiplying the average power generated by the different technologies by the range of values of MCL (%FL) found in literature.
[2] Calculated by multiplying the average LHV efficiency for the different technologies by the range of values of efficiency drop found in literature.
[3] Calculated as the average value of (FL-MCL) divided by the range of values of ramp rate (MW/min) found in literature.
[4] Calculated as the average power generated by the different technologies by the ramp-rate (in % Power/min) found in literature.
[5] Calculated in Steam Pro v25 [33].
[6] Calculated as the house load (MW) divided by the corresponding power generation.
[7] Values found in literature for 'coal power plants' in general. They are assumed to be the same for the different types of coal power plants.
[8] Calculated by dividing the average power generated by the different technologies by the range of values of turning down (min) found in literature.

Table 13
Comparison of the current and future values of specific emission factor at full and MCL for all technologies.

Load	Type of plant	NOx (kg/MWh)				SOx (kg/MWh)				CO (kg/MWh)				CO_2 (kg/MWh)			
		Current values			Future	Current values			Future	Current values			Future	Current values			Future
		Min	Max	Av.	values	Min	Max	Av.	values	Min	Max	Av.	values	Min	Max	Av.	values
Full load	HDGT (SC)[1]	0.14[2]	0.39[2]	0.26[2]	0.05[3]	–	–	–	–	0.04[2]	0.08[2]	0.07[2]	0.03[3]	482[4]	529[4]	500[4]	442[3]
	HDGT (CC)[1]	0.10[2]	0.27[2]	0.18[2]	0.03[3]	–	–	–	–	0.03[2]	0.05[2]	0.05[2]	0.02[3]	334[4]	359[4]	345[4]	303[3]
	Aero-GT[1]	0.22[5]	0.74[5]	0.37[5]	0.05[3]	–	–	–	–	0.18[5]	0.30[5]	0.24[5]	0.14[3]	418[4]	565[4]	495[4]	442[3]
	Sub Coal (Small)	0.34[7]	0.95[7]	0.63[7]	0.20[8]	0.34[7]	2.57[7]	1.45[7]	0.25[8]	0.11[7]	0.18[7]	0.14[7]	0.08[8]	951[7]	1202[7]	1072[7]	670[8]
	Sub Coal (Mid)	0.27[7]	0.77[7]	0.51[7]	0.20[8]	0.28[7]	2.08[7]	1.18[7]	0.25[8]	0.09[7]	0.15[7]	0.11[7]	0.08[8]	771[7]	974[7]	869[7]	670[8]
	Sup Coal (Large)	0.24[7]	0.69[7]	0.45[7]	0.20[8]	0.25[7]	1.86[7]	1.05[7]	0.25[8]	0.08[7]	0.13[7]	0.10[7]	0.08[8]	688[7]	869[7]	775[7]	670[8]
MCL	HDGT (SC)[1]	0.51[2]	0.78[2]	0.62[2]	N.A.	–	–	–	N.A.	0.26[2]	3.09[2]	1.15[2]	N.A.	640[4]	801[4]	711[4]	N.A.
	HDGT (CC)[1]	0.27[2]	0.65[2]	0.37[2]	N.A.	–	–	–	N.A.	0.14[2]	2.17[2]	0.75[2]	N.A.	340[4]	591[4]	417[4]	N.A.
	Aero-GT[1]	0.29[5]	1.01[5]	0.62[5]	N.A.	–	–	–	N.A.	2.48[6]	7.22[6]	3.34[6]	N.A.	572[4]	1153[4]	715[4]	N.A.
	Sub Coal (Small)	0.17[7]	0.53[7]	0.33[7]	N.A.	0.25[9]	2.51[9]	1.35[9]	N.A.	0.07[7]	0.11[7]	0.08[7]	N.A.	1111[7]	1404[7]	1252[7]	N.A.
	Sub Coal (Mid)	0.13[7]	0.36[7]	0.24[7]	N.A.	0.20[9]	1.97[9]	1.06[9]	N.A.	0.05[7]	0.08[7]	0.06[7]	N.A.	873[7]	1103[7]	984[7]	N.A.
	Sup Coal (Large)	0.10[7]	0.29[7]	0.19[7]	N.A.	0.18[9]	1.73[9]	0.93[9]	N.A.	0.05[7]	0.07[7]	0.06[7]	N.A.	768[7]	971[7]	866[7]	N.A.

[1] Emissions were entered for each gas turbine as particles per million (ppm) in GT-Pro v25. Then, GT-Pro was used to estimate the specific emission factor in kg/MWh.
[2] Data extracted from manufacturers, Refs.: [33,35–40,73–77].
[3] Ref.: [78].
[4] Calculated in GT-Pro v25 assuming pure methane as the fuel for all gas turbines.
[5] Data extracted from manufacturers, Refs.: [33,62–68].
[6] Estimated using data extracted from manufacturers and the method proposed by Hung at part load in [79].
[7] Used the method proposed by EEA [80] for estimating absolute emissions and Steam-Pro v25 for estimating specific emissions.
[8] Ref.: [81].
[9] Ref.: [82].

than other technologies. The longer the shutdown prior to start, the lower the metal temperatures and the longer the start-up time [20]. Start-up times of Aero-GT and heavy duty gas turbines in simple cycle are largely unaffected by the shutdown time as no heat transfer is required for operation. Start-up times are expected to significantly reduce in the future. In coal power plants, expected start-up times would range from 115–140 min in hot start-ups to 370–420 min in cold start-ups. In combined cycles, future start-ups would be 25 min in hot start-ups and 120 min in cold start-ups. Finally, expected start-up times are 2 min for Aero-GT and 11 min for HDGT simple cycles.

A comparison of current and future values of specific emission factors for the different technologies at full load is shown in Fig. 11. At full load, specific emission factors for all pollutants are in most cases higher in coal-fired power plants than in gas-fired power plants. On average, NOx, CO and CO_2 emissions are 50–100% higher in coal plants than in natural gas plants. The only exception was the Aero-GT, which presented equal or even higher specific emission factors of NOx and CO than coal plants at full load. Since SOx emissions are directly related to the sulfur content of the fuel and this is negligible for natural gas, the SOx emissions of gas turbines were found to be near zero [80].

Table 14
Comparison of the current and future values of specific emission factor at hot and cold starts for all technologies.

Type of start	Type of plant	NOx (kg/MW)				SOx (kg/MW)				CO (kg/MW)			
		Current values			Future values	Current values			Future values	Current values			Future values
		Min	Max	Av.		Min	Max	Av.		Min	Max	Av.	
Hot	HDGT (SC)[1]	0.03	0.14	0.07	N.A.	–	–	–	N.A.	0.2	0.8	0.4	N.A.
	HDGT (CC)[1]	0.02	0.10	0.05	N.A.	–	–	–	N.A.	0.1	0.6	0.3	N.A.
	Aero-GT[2]	0.05	0.09	0.07	N.A.	–	–	–	N.A.	0.5	8.7	5.7	N.A.
	Coal (all)[3]	0.90	1.35	1.12	N.A.	1.8	2.7	2.2	N.A.	–	–	–	N.A.
Cold	HDGT (SC)[1]	0.3	1.2	0.6	N.A.	–	–	–	N.A.	0.7	2.6	1.3	N.A.
	HDGT (CC)[1]	0.2	0.9	0.4	N.A.	–	–	–	N.A.	0.4	1.8	0.9	N.A.
	Aero-GT[2]	0.05	0.09	0.07	N.A.	–	–	–	N.A.	0.5	8.7	5.7	N.A.
	Coal (all)[3]	1.35	1.80	1.57	N.A.	3.5	8	5.7	N.A.	–	–	–	N.A.

[1] Absolute emissions per start were collected from various Refs. [41,56,83–85]. Specific emissions (kg/MW) were estimated using outputs from GT-Pro v25 for the different gas turbines.
[2] Absolute emissions per start were collected from various Refs. [86,87]. Specific emissions (kg/MW) were estimated using outputs from GT-Pro v25 for the different Aero-derivative gas turbines.
[3] Data taken from [80,88].

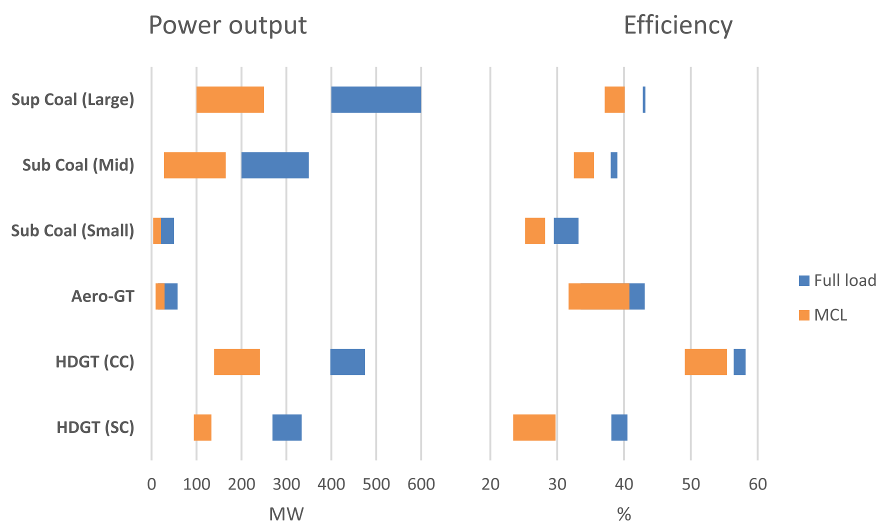

Fig. 8. Comparison of the power output and efficiency at full load and minimum complaint load (MCL) for the different technologies.

The technology offering the lowest specific emission factors for all pollutants was the HDGT in combined cycle, while the technology offering the highest specific emission factors for all pollutants was the small-scale sub-critical coal power plant. Specific emission factors are expected to reduce in the future for all pollutants in gas- and coal-fired power plants. On average, future reductions in specific emission factors for gas and coal plants are expected to be 80% for SOx, 70% for NOx, 40% for CO and 20% for CO_2.

Specific emission factors for the different technologies at full load are compared to those at minimum complaint load in Fig. 12. In gas-fired power plants, emissions at minimum complaint load are on average 1.5–15 times higher than those at full load. While the increase in emissions at MCL vs full load are on average 50–100% for NOx and CO_2, they are 15 times higher for CO. At MCL, gas turbines produce lower or equal absolute NOx and CO_2 emissions (e.g. ppm or kg/s) than at full load due to lower combustion temperatures and volumes of fuel burned. However, simultaneously they also produce lower power at a lower efficiency. Since the reduction in power and efficiency is stronger than the reduction in absolute emissions, the NOx and CO_2 specific emission factors at MCL are higher than at full load. On the other hand, the significant increase in CO emissions is attributed to the incomplete combustion of the natural gas (e.g. inadequate burning, mixing or quenching of the air before complete combustion) occurring at part load in gas turbines [79]. For coal-fired power plants, NOx, SOx and CO specific emission factors reduce at MCL compared to the full load and according to literature are to a large extent proportional to the load [80,82]. In contrast, CO_2 emissions in coal plants are higher at MCL than at full load, similarly to gas plants. On average, it was found that at MCL gas turbines produced more NOx and CO emissions than coal plants, but less CO_2 and SOx emissions.

The specific emission factors at hot and cold starts for the different technologies are shown in Fig. 13. On average, emissions during cold starts for all technologies are found to be 2 to 16 times higher than during hot starts. Increases in emissions between cold and hot starts are particularly large for NOx and CO emissions in gas plants (viz. 16- and 6-fold, respectively) as well as for SOx emissions in coal plants (viz. 8-fold). The increase in NOx, SOx and CO emissions during cold starts vs hot starts is attributed to the longer time during startup that emission control technologies need to properly operate, particularly below the minimum complaint load [89].

The improvements between the current state of the art and the future values of flexibility parameters and emissions for the different technologies are summarized in Fig. 14. These improvements are significant (35–100% compared to state of the art) and reflect the urgent need for improving the flexibility and emissions of conventional power plants to adapt to the future with higher renewables. Future gas

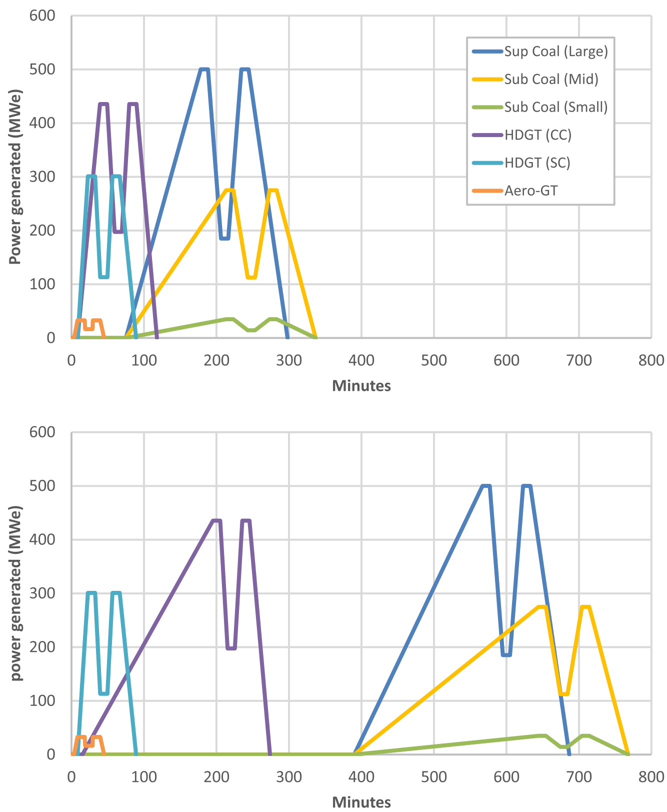

Fig. 9. Comparison of an average full cycle time after a hot start (top) and a cold start (bottom) for the different technologies.

and steam turbines are expected to have twice as much number of starts, 70–100% faster ramp-up rates, 35–70% faster start-up rates and 35–60% lower MCL than current state of the art. These increased gradients, number of starts and lower minimum load may help conventional generation to offer short-term backup to renewables, but may also put significant stress on plant systems. Finally, specific emission factors in gas and coal plants are expected to reduce in the future by 80% for SOx, 70% for NOx, 40% for CO and 20% for CO_2.

7. Energy security and the ability to back-up renewables

A news article in the Welt in Germany [64], raised the threat of energy security experienced in Germany during January 2017. On 24 January 2017, wind produced less than 1 GW for almost the whole day and solar helped to lift the total to 3 GW at midday leaving the remaining 83 GW demand to be provided by conventional power plants. This situation was similar between 16 and 26 January 2017. A solution was provided by nuclear and coal plants.

The critical question is whether improved flexibility conventional is sufficient to back-up highly variable renewables. To answer this question, a simple experiment has been carried out. Firstly, a typical wind and solar power generation curve in Germany is taken as a reference. A cumulative 48-h curve describing the wind and solar power generation in two consecutive random days in the spring of 2016 is used (see Fig. 15, left).

This curve is normalized and then scaled up and down to produce generic renewable profiles that match exactly the power output of the different conventional plants. This ensures that a conventional plant could cover up to 100% of its corresponding generic renewable profile. Then, the ability of the different technologies to back-up renewables is assessed. This ability is defined as the ratio between the combined conventional and renewable power generation and the renewable power generation running at full load for a time period of 48 h:

$$Backup\ ability = \frac{(MWh)_{conventional} + (MWh)_{renewable}}{(MW)_{renewable} \bullet 48 hours} \tag{1}$$

where $(MWh)_{conventional}$ is the energy generated by the conventional plant in megawatt-hours assuming the flexibility characteristics described in previous sections; $(MWh)_{renewable}$ is the energy generated in megawatt-hours by the corresponding generic renewable; and $(MW)_{renewable}$ is the power capacity in megawatt of the generic renewable, which is the same power capacity as that of the conventional power plant. An example of the back-up ability of an average state of the art supercritical coal power plant can be seen in (see Fig. 15, right). In essence, backup ability is equal to 1 when conventional power is able to completely backup the renewable fluctuations. As seen in Fig. 15, there are white portions of the 48 h not covered by blue (renewable) and orange (conventional). The degree of deviation from 1 is therefore a measure of the lack of backup.

For calculating the back-up ability, a Monte Carlo model was created. This Monte Carlo model estimates the back-up ability of the different technologies by considering not only their corresponding design and flexibility characteristics, but also the variation in those parameters. The Monte Carlo model uses a Latin Hypercube of 1000 bins and perform one million trials. Obtained results for state of the art and future technologies are shown in Fig. 16. Results show that, under the considered assumptions, state of the art gas turbines offer a larger ability to back-up renewables than state of the art coal power plants. While the estimated back-up ability of gas turbines ranges from 92% (+7%, −23%) in Aero-GT to 95% (± 3%) HDGT in combined cycle, for coal power plants it ranged from 85% (± 7.5%) in subcritical plants to 87% (± 5%) in supercritical plants. The largest variation in the

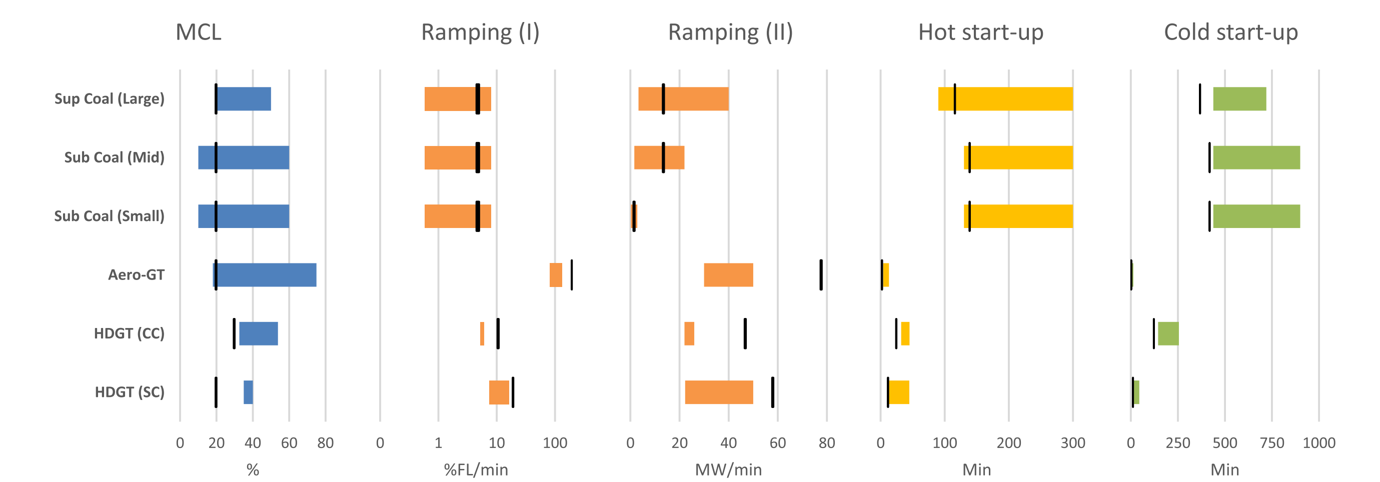

Fig. 10. Comparison of different flexibility processes for the different technologies. Black bars represent possible future values.

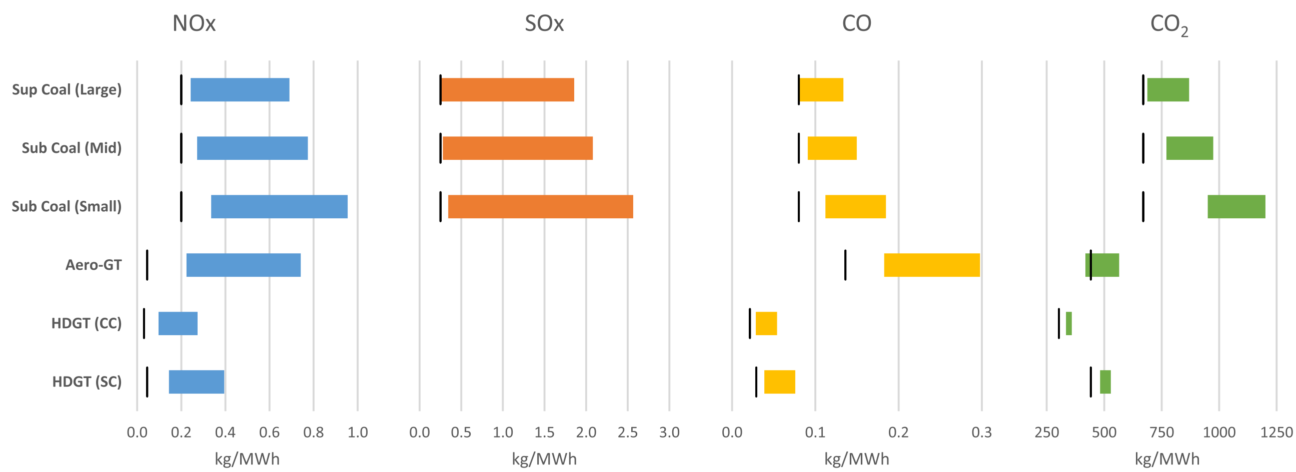

Fig. 11. Comparison of specific emission factors for the different technologies at full load. Black bars represent possible future values.

estimated back-up ability was found for the Aero-GT (+7%, −23%) owing to the large variation in minimum compliant load for that technology. Results also show that by improving flexibility a higher back-up ability can be expected in all future technologies compared to state of the art technologies. Back-up ability of future coal power plants can grow up to 95%, while it can grow to 97% and 99% for future HDGT in combined cycle and Aero-GT, respectively.

8. Conclusions

This paper firstly describes the current state of the art of gas- and coal-fired power plants in terms of design and operational conditions. Secondly, it reviews literature on current and possible future emissions and flexibility characteristics of various operational processes for those cases.

Gas turbines are found to be more efficient than coal power plants at full load and at minimum complaint load. However, their efficiency range is broader and their minimum power load is higher (except for the Aero-GT) than those of coal power plants. Gas turbines are not only more efficient, but also faster than coal power plants. Start-up times in gas turbines range between 4–45 min in hot starts and 4–250 min in cold starts, while start-up times in coal power plants range between 100–300 min in hot starts and 450–900 min in cold starts. Similarly, full cycle times for gas turbines range between 45 and 280 min, while for coal power plants range between 350 and 800 min. Ramping rates are also generally higher in gas turbines than in coal power plants. While in gas turbines they range between 25 and 50 MW/min (representing 5–100% of the full load per minute), in coal power plants they range between 2 and 40 MW/min (representing 0.5–8% of the full load per minute).

In general, technologies relying on heat transfer for power generation such as coal power plants and combined cycles are generally more affected by the shutdown time before the start than other technologies. The longer the shutdown prior to start, the lower the metal temperatures and the longer the start-up time. Start-up times of Aero-GT and heavy duty gas turbines in simple cycle are largely unaffected by the shutdown time as no heat transfer is required for operation.

At full load, NOx, CO and CO_2 emissions are on average 50 to 100% higher in coal plants than in gas plants. The only exception was the Aero-GT, which presented equal or even higher specific emission factors of NOx and CO than coal plants. On average, it was found that at the minimum complaint load (MCL) gas turbines produced more NOx and CO emissions than coal plants, but less CO_2 and SOx emissions. Furthermore, emissions during cold starts for all technologies are found to be 2–16 times higher than during hot starts.

The improvements between the current state of the art and the future values for the different technologies are significant (35–100% compared to state of the art) and reflect the urgent need for improving the flexibility and emissions of conventional power plants to adapt to the future with higher renewables. Future gas and steam turbines are

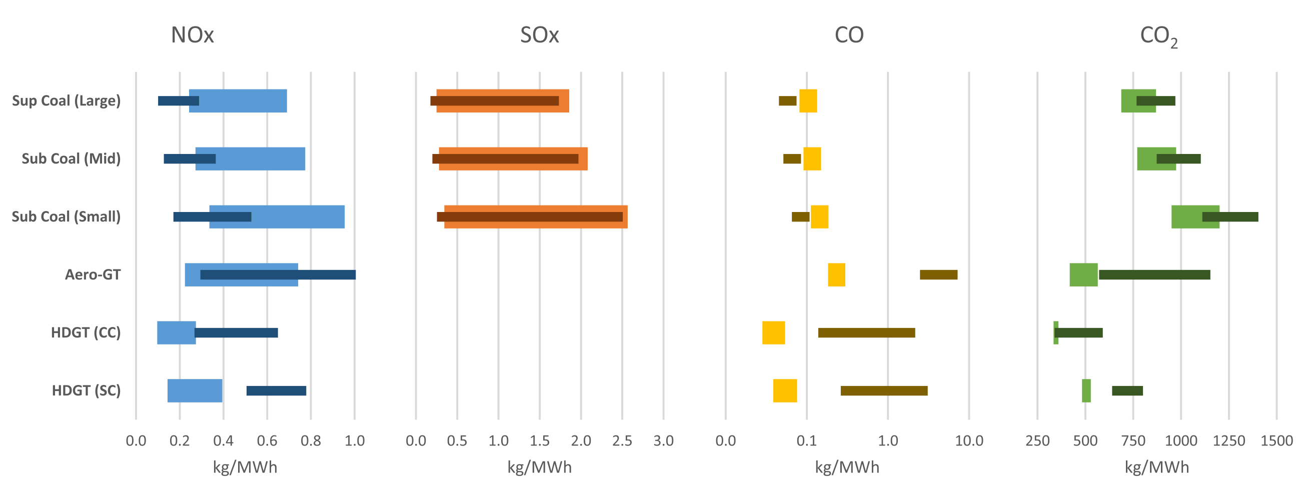

Fig. 12. Comparison of specific emission factors for the different technologies at full load and MCL. Light thicker bars represent emission factors at full load, dark narrower bars represent emission factors at MCL. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

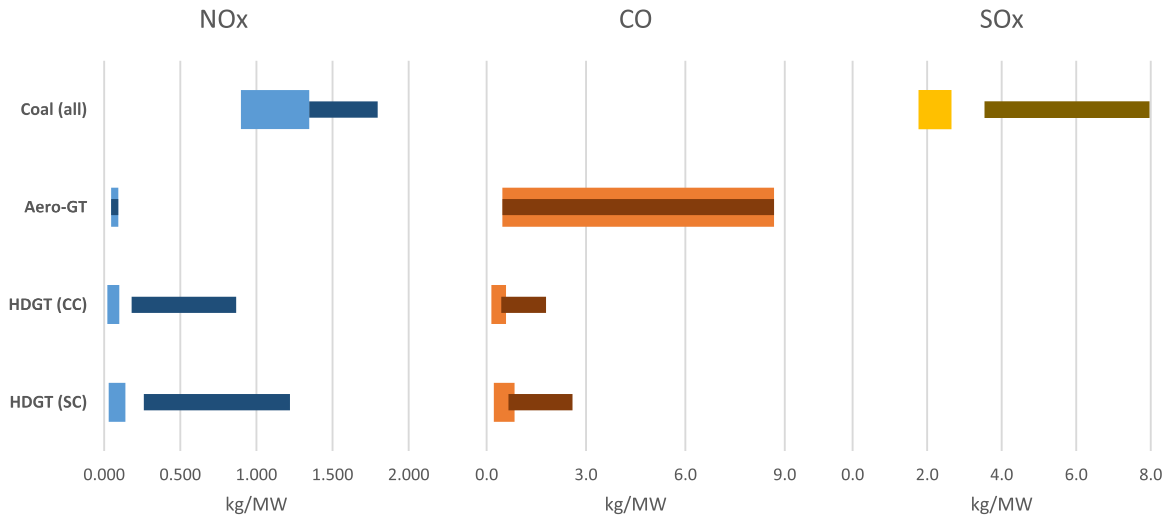

Fig. 13. Comparison of specific emission factors for the different technologies at hot and cold starts. Light bars represent emission at hot starts, dark bars represent emission at cold starts. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

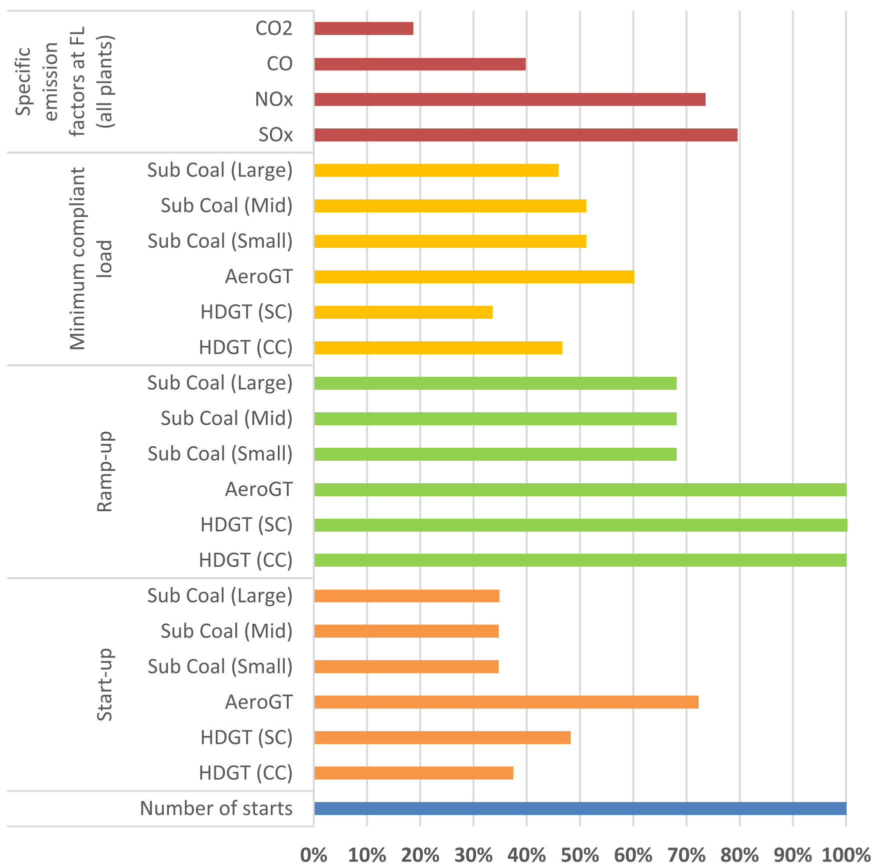

Fig. 14. Improvement in flexibility and emissions between current and future values.

expected to have twice as many starts, 70–100% faster ramp-up rates, 35–70% faster start-up rates, 35–60% lower minimum compliant load and 20–80% lower emissions than current state of the art. These increased gradients, number of starts, lower minimum load and emissions may help conventional generation to offer short-term backup to renewables. Results of a Monte Carlo simulation showed that by improving flexibility a higher back-up ability can be expected in all future technologies compared to state of the art technologies. The back-up ability (defined as the ratio between the combined conventional and renewable power generation and the renewable power generation running at full load for a time period of 48 h) of future coal power plants can grow from 85% to 95%, while it can grow from 95% to 97% in combined cycle and from 92% to 99% in Aero-GT. These findings are expected to offer important insights to guide research and assess technology improvements as well as to provide inputs for long-term energy models assessing future energy systems.

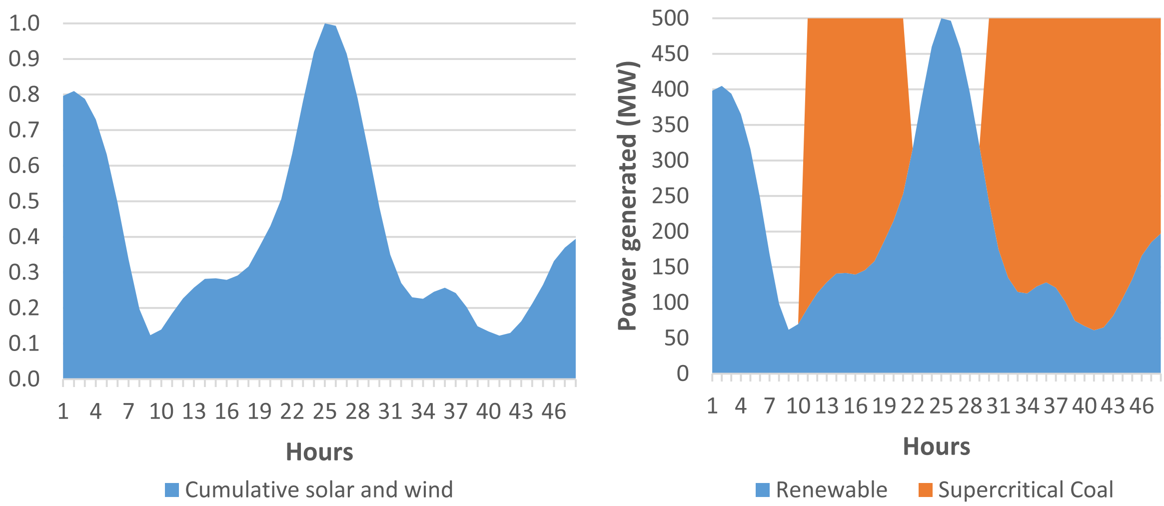

Fig. 15. Left: normalized power generation curve of wind and solar in Germany for 48 random hours from [90]. **Right**: back-up ability of an average state of the art supercritical coal plant.

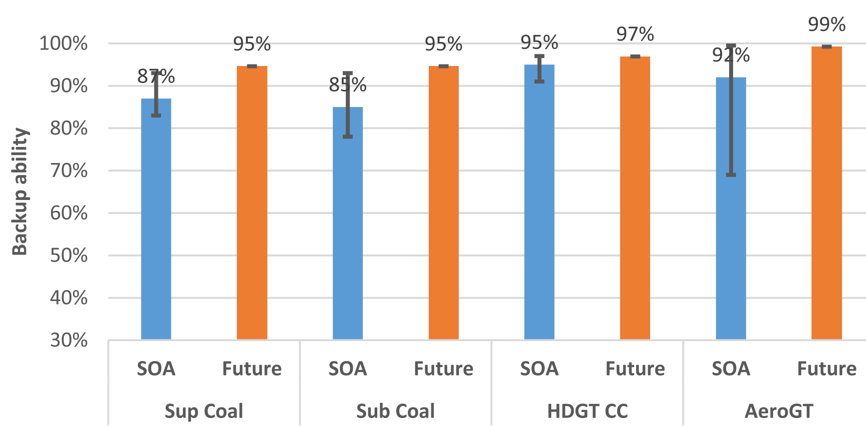

Fig. 16. Back-up ability of state of the art (SOA) and future technologies.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 653941). The authors would like to thank and acknowledge the contributions by the other project members: Alexander Wiedermann, Martin Hughes, Petr Mestanek, Pavel Panek and Mauro Maccio and the UCG members: Sonia Clarena Baron, Ivan Dudurych, Oliver Then, Jose Miguel Berrio Soler, Ales Laciok, Martin Pistora and Karina Medved.

References

[1] European Commission. Energy roadmap 2050 European Commission; 2011. ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0885:FIN:EN:PDF⟩.
[2] IEA. Energy technology perspectives (ETP). Harnessing electricity's potential. International Energy Agency (IEA). Paris; 2015.
[3] IEA. World energy outlook 2016. International Energy Agency, (IEA). OECD/IEA 2016; 2016. ⟨www.iea.org⟩.
[4] Randell T. World energy hits a turning point: solar that's cheaper than wind, Bloomberg; 2016. ⟨https://www.bloomberg.com/news/articles/2016-12-15/world-energy-hits-a-turning-point-solar-that-s-cheaper-than-wind⟩.
[5] Western Governors' Association . Meeting renewable energy targets in the west at least cost: the integration challenge. Western Governors' Association; 2012.
[6] Henderson C. Increasing the flexibility of coal-fired power plants. London: IEA Clean Coal Centre; 2014.
[7] Glensk B, Rosen C, Bachmann Schiavo R, Rabiee S, Madlener R, De Doncker R. Economic and technical evaluation of enhancing the flexibility of conventional power plants. E.ON energy research center series. Vol. 7. Issue 3; 2015.
[8] NETL . Impact of load following on power plant cost and performance: literature review and industry interviews. National Energy Technology Laboratory (NETL). U.S. Department of Energy; 2012.
[9] Brinkman G, Kumar N, Besuner P, Agan D, Lefton S. Impacts of wind and solar on fossil-fueled generators. Oak Ridge: National Renewable Energy Laboratory (NREL); 2012.
[10] Hentschel J, Babic U, Spliethoff H. A parametric approach for the valuation of power plant flexibility options. Energy Rep 2016;Bd. 2:40–7.
[11] IEA . Technology roadmap, energy storage. Paris: International Energy Agency (IEA); 2014 https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf.
[12] P. Kelly-Detwiler, „One Expert's View On The Near-Term Future Of Energy Storage," Forbes. https://www.forbes.com/sites/peterdetwiler/2016/06/06/one-experts-view-on-the-near-term-future-of-energy-storage/#47b0ea6756f6, 2016.
[13] IEA . The power of transformation – wind, sun and the economics of flexible power. Paris: International Energy Agency (IEA), OECD/IEA; 2014, ISBN: 978 92 64 20803 2.
[14] Becker G, Wagenhäuser H. Das europäische Verbundnetz. Entstehung, heutige Strukturen und zukünftige Herausforderungen. Munich: Technik in Bayern; 2016.
[15] NREL . Renewable Electricity Futures Study. National Renewable Energy Laboratory (NREL), U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; 2012 http://www.nrel.gov/analysis/re_futures/.
[16] Helbig K, Banaszkiewicz M, Mohr W. Advanced lifetime assessment and stress control of steam turbines. Power-Gen Eur 2016:2016.
[17] Miller B. Clean coal engineering technology. Elsevier; 2011 http://app.knovel.com/hotlink/toc/id:kpCCET000B/clean-coal-engineering/clean-coal-engineering.
[18] Burnard K, Bhattacharya S. Power generation from coal. Ongoing developments and outlook. Paris: Information Paper. International Energy Agency (IEA); 2011 https://www.iea.org/publications/freepublications/publication/Power_Generation_from_Coal2011.pdf.
[19] Ruchti C, Olia H, Franitza K, Ehrsam A, Bauver W. Combined cycle power plants as ideal solution to balance grid fluctuations. In: Kraftwerkstechnisches Kolloquium. Dresden; 2011.
[20] Gülen S, Kim K. Gas turbine combined cycle dynamic simulation: a physics based simple approach. J Eng Gas Turbines Power 2014:136, [pp. 136: 011601-01160115].
[21] Wacek E, Ferguson W. Application of the latest aeroderivative gas turbine technology. In: Proceedings of the IAGT; 2009.

[22] Schröder A, Kunz F, Meiss J, Mendelevitch R, von Hirschhausen C. Current and prospective costs of electricity generation until 2050. Berlin: Deutsches Institut für Wirtschaftsforschung (DIW); 2013.
[23] Sanchez Fernandez E, Sanchez del Rio M, Chalmers H, Khakharia P, Goetheer E, Gibbins J, et al. Operational flexibility options in power plants with integrated post-combustion capture. Int J Greenh Gas Control 2016;Bd. 48:275–89.
[24] Brouwer A, van den Broek M, Seebregts A, Faaij A. Operational flexibility and economics of power plants in future low-carbon power systems. Appl Energy 2015;Bd. 156:107–28.
[25] Kondziella H, Bruckner T. Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. Renew Sustain Energy Rev 2016;Bd. 53:10–22.
[26] Lund P, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;Bd. 45:785–807.
[27] Graichen P, Kleiner M, Buck M. Energy transition in the power sector in Europe: state of Affairs in 2015 – review of the developments and outlook for 2016. Berlin: Agora Energiewende; 2016.
[28] Ireneusz P. VDE-Studie: erneuerbare Energie braucht flexible Kraftwerke – Szenarien bis 2020. Verband der Elektrotechnik Elektronik Informationtechnik (VDE); 2013.
[29] Brinckerhoff Parsons. Technical assessment of the operation of coal & gas fired plants. London: UK Deparment of Energy and Climate Change (DECC); 2014.
[30] McCoy. McCoy power reports. McCoy Power Reports; 2015.
[31] Ducker M. The fall of the F-class turbine; 21 August 2015. [Online]. Available: ⟨http://www.power-eng.com/articles/print/volume-119/issue-8/features/the-fall-of-the-f-class-turbine.html⟩. [Accessed on 12.07.16].
[32] Matta R, Mercer G, Tuthill R. Power systems for the 21st century – "H" gas turbine combined-cycles. GE Power Syst 2000, [GER-3935B].
[33] Thermoflow. GT Pro 25 & ST Pro 25; 2016.
[34] Chase D, Kehoe P. GE combinedy-cycle product line and performance. GE Power Syst 2000, [GER-3574G].
[35] Tanimura S, Akamatsu S, Sato K, Koeneke C. New dry low NOx combustor for Mitsubishi M501/701G. In: Proceedings of the ASME 2007 power conference. San Antonio, Texas; 2007.
[36] Arimura H, Iwasaki Y, Shiozaki S, Fukuizumi Y, Koeneke C. Update on Mitsubishi's large frame 50 and 60 Hz G-series gas turbine upgrades. In: Proceedings of the ASME Turbo Expo 2007: power for land, sea, and air. Montreal; 2007.
[37] Xia J, Antos R. SGT6-5000F (W501F) 3 million hours fleet operational experience. In: Proceedings of the power-gen international 2006. Orlando; 2006.
[38] Siemens. Gas turbine SGT5-4000F; 2016. [Online]. Available: ⟨http://www.energy.siemens.com/hq/en/fossil-power-generation/gas-turbines/sgt5-4000f.htm⟩. [Accessed on 16.06.2016].
[39] MHPS. M701F series gas turbine; 2016. [Online]. Available: ⟨https://www.mhps.com/en/products/thermal_power_plant/gas_turbin/lineup/m701f.html⟩. [Accessed on 20.06.16].
[40] GE. Heavy-duty gas turbines; 2016. [Online]. Available: ⟨https://powergen.gepower.com/products/heavy-duty-gas-turbines.html⟩. [Accessed on 20.06.16].
[41] Bivens R. Startup and shutdown NOx emissions from combined cycle combustion turbine units. EPRI CEM User Group Meeting; 2002. ⟨http://www.rmb-consulting.com/papers/SUSD%20Chicago%20Paper.pdf⟩.
[42] Corboz D, Südland M, Bok J. Operational benefits of the GT24/GT26 plant in a volatile power environment. In: Proceedings of the PowerGen; 2004.
[43] Wick J. Advanced gas turbine technology GT26; 2006.
[44] Henkel N, Schmid E, Gobrecht E. Operational flexibility enhancements of combined cycle power plants. In: Proceedings of the Power-Gen 2008, Kuala Lumpur; 2008. ⟨http://www.energy.siemens.com/hq/pool/hq/energy-topics/pdfs/en/combined-cycle-power-plants/OperationalFlexibilityEnhancementsofCombinedCyclePowerPlants.pdf⟩.
[45] Siemens. Gas turbine SGT5-8000H; 2016. [Online]. Available: ⟨http://www.energy.siemens.com/hq/en/fossil-power-generation/gas-turbines/sgt5-8000h.htm⟩. [Accessed on 20.06.16].
[46] Siemens. Gas turbine SGT6-4000F; 2016. [Online]. Available: ⟨http://www.energy.siemens.com/hq/en/fossil-power-generation/gas-turbines/sgt5-4000f.htm⟩. [Accessed on 20.06.16].
[47] GE-Alstom. GT24/GT26 gas turbines; 2016. [Online]. Available: ⟨http://alstomenergy.gepower.com/Global/Power/Resources/Documents/Brochures/gt24-and-gt26-gas-turbines-epslanguage=en-GB.pdf⟩. [Accessed on 20.06.16].
[48] Pyros G, Ota K, Kishine T, Koeneke C, McDeed D, Freemen J Fast start combined cycle based on the M501GAC. In: Proceedings of the Power-Gen 2012. Orlando; 2012.
[49] Balling L, Tomschi U, Pickard A. CC project references for cycling and grid support: live examples from projects in the Netherlands, France, Austria, the UK and Denmark. In: Proceedings of the Power-Gen 2010. Amsterdam; 2010.
[50] Feldmüller A, Zimmerer T, Roehr F. From base to cycling operation – innovative operational concepts for CCPPs. In: Proceedings of the Power-Gen Europe 2015. Amsterdam; 2015.
[51] Nag P, Little D, Teehan D, Wetzl K, Elwod D. Low load operational flexibility for siemens G class gas turbines. In: Proceedings of the Power-Gen international 2008. Florida; 2008.
[52] Kovac J. Advanced SGT6-5000F development. In: Proceedings of the Power-Gen international 2008. Orlando; 2008.
[53] GE. POWERing the World, GE power; 2016. ⟨https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/documents/product/2016-gas-power-systems-products-catalog.pdf⟩.
[54] Gülen S, Jones C. GE's next generation CCGT plants: operational flexibility is the key. Mod Power Syst 2011.
[55] Domenichini R, Mancuso L, Ferrari N, Davison J. Operating flexibility of power plants with carbon capture and storage (CCS). In: Proceedings of the energy procedia and GHGT-11; 2010.
[56] California Energy Commission. GWF Tracy combined cycle power plant project. Application for Certification (08-AFC-07). California Energy Commission; 2010 ⟨http://www.energy.ca.gov/2010publications/CEC-800-2010-002/CEC-800-2010-002-PMPD.PDF⟩.
[57] Jordan G, Venkataraman S. Analysis of cycling costs in western wind and solar integration study. Oak Ridge: National Renewable Energy Laboratory (NREL); 2012.
[58] GE Energy . Western wind and solar integration study. National Renewable Energy Laboratory (NREL); 2010.
[59] EA . Vancouver island generation project. Canada: Environmental Assessment Office, British Columbia; 2002.
[60] Nidras P, Galanis P, Torres-Moncayo F. Energy price limits for the wholesale electricity market in Western Australia. Melbourne: Jacobs Group (Australia) Pty Limited; 2015.
[61] Boyce M. Gas turbine engineering handbook, 4th ed.. Elsevier; 2012 http://app.knovel.com/hotlink/toc/id:kpGTEHE017/gas-turbine-engineering-2/gas-turbine-engineering-2.
[62] GE. Aeroderivative gas turbines, GE power & water; 01 July 2016. [Online]. Available: ⟨https://powergen.gepower.com/products/aeroderivative-gas-turbines.html⟩. [Accessed on 01.07.16].
[63] Industrial Info . Gas turbine world 2014–2015 handbook. Industrial Info Resources; 2015.
[64] Solar Turbines. Titan 250, solar turbines; 01 July 2016. [Online]. Available: ⟨https://mysolar.cat.com/en_US/products/oil-and-gas/gas-turbine-packages/compressor-sets/titan-250.html⟩. [Accessed on 01.07.16].
[65] Kawasaki. Gas turbines for power generation, Kawasaki gas turbine Europe GmbH; 2012. ⟨https://www.vgb.org/vgbmultimedia/Kawasaki+Pr%C3%A4sentation+2013_deutsch+inkl_+L30+%5BKompatibilit%C3%A4tsmodus%5D-p-6540.pdf⟩.
[66] Siemens. Siemens gas turbines, Siemens; 01 July 2016. [Online]. Available: ⟨http://www.energy.siemens.com/hq/en/fossil-power-generation/gas-turbines/⟩. [Accessed on 01.07.16].
[67] Solar Turbines. Titan 130, solar turbines; 01 July 2016. [Online]. Available: ⟨https://mysolar.cat.com/en_US/products/power-generation/gas-turbine-packages/titan-130.html⟩. [Accessed on 01.07.16].
[68] Tanaka R, Koji T, Ryu M, Matsuoka A, Okuto A. Development of high efficient 30 MW class gas turbine: the Kawasaki L30A. In: Proceedings of the ASME turbo expo 2012. Copenhagen; 2012.
[69] Badeer G. GE aeroderivative gas turbines – design and operating features [Report GER-3695E]. Evendale: GE Power Systems; 2001.
[70] Venkataraman S, Jordan G, O'Connor M, Kumar N, Lefton S, Lew D, et al. Cost-benefit analysis of flexibility retrofits for coal and gas-fueled power plants. Oak Ridge: National Renewable Energy Laboratory; 2013.
[71] Finkenrath M, Smith J, Volk D. CCS Retrofit. Analysis of the globally installed coal-fired power plant fleet. Paris: International Energy Agency (IEA); 2012 https://www.iea.org/publications/freepublications/publication/CCS_Retrofit.pdf.
[72] Müller S. The power of transformation. Wind, sun and the economics of flexible power systems. Paris: International Energy Agency (IEA); 2014.
[73] Becker B, Thien V. High-efficiency gas turbines operating in intermediate duty. In: Proceedings of the international gas turbine congress. Tokyo; 2003.
[74] FPL . Technical evaluation and preliminary determination, Riviera Plant Conversion Project. Florida Power and Light Company (FPL); 2009 https://www.dep.state.fl.us/air/emission/construction/fplriviera/TECH006.pdf.
[75] Becker B. Upgrade of the Siemens gas turbine V94.3A. In: Proceedings of the Power-Gen Europe 2004; 2004.
[76] Huth M. Design of the combustion system for the SGT5-8000H and first experiences in the Irsching power plant. In: Proceedings of the VGB-Fachtagung, Gasturbinen und Gasturbinenbetrieb. Mannheim; 2009.
[77] Acuti M, Gatti R, Traverso R. Ansaldo energia brand new applications in minimum load reduction for AE94.3A and in the peak energy market for AE94.2. Ansaldo Energia; 2006. ⟨http://pennwell.sds06.websds.net/2012/cologne/pgnp/papers/T3S2O5-paper.pdf⟩.
[78] Goldstein L, Hedman B, Knowles D, Freedman S, Woods R, Schweizer T. Gas-fired distributed energy resource technology characterizations. Golden: National Renewable Energy Laboratory (NREL); 2003.
[79] Hung W. Carbon monoxide emissions from gas turbines as influenced by ambient temperature and turbine load. In: Proceedings of the international gas turbine and aeroengine congress and exposition, transactions of the american society of mechanical engineers (ASME). Cologne; 1992.
[80] EEA . EMEP/EEA air pollutant emission inventory guidebook. European Environment Agency (EEA); 2016 https://www.eea.europa.eu/publications/emep-eea-guidebook-2016.
[81] IEA . Technology roadmap: high efficiency, low-emissions coal-fired power generation. Paris: International Energy Agency (IEA); 2012.
[82] Brinkman G. Emission impact of fossil fuel unit cycling. Oak Ridge: National Renewable Energy Laboratory (NREL); 2011 http://wind.nrel.gov/public/WWIS/Emissions.pdf.
[83] Environmental Resources Management . ESC Harrison County power, air permit application, combined-cycle power plant project, Clarksburg, Harrison County, West Virginia. Environmental Resources Management; 2016 http://www.dep.wv.gov/daq/Documents/December%202016%20Applications/033-00264_APPL_R14-0036.pdf.
[84] California Energy Commission . San Gabriel generating station, application for

certification. California Energy Commission; 2007 http://www.energy.ca.gov/sitingcases/sangabriel/documents/applicant/afc-cd/AFC_Volume-1/7.1%20Air%20Quality.pdf.
[85] EPA . Prevention of significant deterioration greenhouse gas permit application for the Tenaska Roans Prairie generating station. US Environmental Protection Agency (EPA); 2013 https://archive.epa.gov/region6/6pd/air/pd-r/ghg/web/pdf/tenaska-roans-prairie-generating-station-app.pdf.
[86] Witherspoon L. Emission estimates at start-up, shutdown, and commissioning for SoLoNOx combustion products. Solar Turbines Inc.; 2012.
[87] Environmental Resources Management . Atlantic coast pipeline project permit application Marts Compressor Station Lewis County, WV. Environmental Resources Management; 2015.
[88] Lew D, Brinkman G, Kumar N, Lefton S, Jordan G, Venkataraman S. Finding flexibility, cycling the conventional fleet. IEEE Power Energy Mag 2013.
[89] Oates D, Jaramillo P. Production cost and air emissions impacts of coal cycling in power systems with large-scale wind penetration. Environ Res Lett 2013;Bd. 8(Nr. 024022).
[90] European Energy Exchange AG. EEX-Transparenzplattform. EEX-Transparenzplattform. European Energy Exchange AG; 2016. [Online]. Available: ⟨https://www.eex-transparency.com/⟩.