Emission footprint analysis of dispatchable gas-based power generation technologies

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Introduction

The European Green Deal sets the ambitious objective of making the EU carbon-neutral by 2050 [1]. To achieve this objective, The EU recently introduced taxonomy regulations aiming to direct investments toward sustainable projects and activities [2]. Within the energy sector, this paradigm change requires a transition towards sustainable power generation technologies and more comprehensive environmental considerations. For sustainable energy systems dominated by renewable energy, dispatchable power generation technologies are an essential asset for maintaining the security of supply. Due to their efficiency and operational flexibility, both gas turbines (GT) and gas-fueled reciprocating internal combustion engines (RICE) are well suited for this task. However, despite their similarity, emissions resulting from the operation of GT and RICE are commonly regulated independently, using individual references and metrics (e.g., German BlmSchV [3]). Moreover, publicly available studies and reports (e.g., BAT Reference Document for Large Combustion Plants [4]) typically investigate the emission characteristics of GT and RICE without direct comparison, although both technologies increasingly compete in power projects. Considering both the growing relevance of dispatchable gas-based power generation technologies and the need for more extensive environmental impact considerations, the present study aims to provide a comprehensive emission footprint analysis of GT and RICE using an apples-to-apples metric (i.e., generated mass of a species per electrical output, g/kWhel). In the first part of the study, this apples-to-apples metric is applied to compare current major regulatory frameworks of both technologies (e.g., German BlmSchV, EU BREF, US EPA 40 CFR) and highlights relevant differences. The second part of the study provides a comparative analysis of the emission behavior of both GT and RICE. Representative power plant configurations and operating regimes are considered, i.e., “peaking” and “baseload” operation, for plants with an output between 50 and 200 MWel. The resulting overall emissions of GT and RICE are calculated using an EXCEL-based model framework, which is parameterized using publicly available performance and emission data of both technologies. Similarly, emission reduction technologies (e.g., SCR) are modeled based on literature data. Employing the introduced apples-to-apples metric, the overall emissions of the investigated scenarios and technologies can be compared directly. The final part of the study discusses the environmental footprint of the considered gas-based power generation technologies. The impact of the technology choice and operating scenario on the overall emission footprint is highlighted.
1 Legislation overview

1.1 Utilization of g/kWhel as an apples-to-apples metric for environmental footprint analyses

Regulations and scientific publications commonly employ ppmvd\(^1\), mg/m\(^3\), and also non-SI units as metrics for quantifying emissions from dispatchable gas-based power generation technologies. Emission values are typically normalized to a reference oxygen content to account for dilution of pollutants due to excess air and varying oxygen contents in the exhaust gas. In most cases, emissions from GT and RICE are normalized to different oxygen contents\(^2\). As a result, normalized emission values cannot be compared directly. Furthermore, even when the same reference oxygen content is utilized, emissions reported in ppmvd or mg/m\(^3\) do not account for power generation efficiency associated with the emission release. The present study uses g/kWhel as an apples-to-apples metric for GT and RICE emissions to overcome these limitations. On the one hand, this metric accounts for the mass-based emission release, which is essential for environmental impact considerations. On the other hand, it considers the electrical efficiency of the investigated power generation technology, which is a primary indicator for a comprehensive technology comparison.

1.2 Comparison of major regulatory frameworks of GT and RICE

As they impose binding constraints on power plant operators, regulations have an important impact on the emission footprint of gas-based power generation technologies. However, significant variations in scope and strictness can be observed when considering current emission regulations for GT and RICE from a national to a global level. To account for this variety, the present study examines emission guidelines issued by the World Bank\(^3\) (WB), environmental footprint analyses of dispatchable gas-based power generation technologies. Emission values\(^9\) depending on the net electrical conversion to g/kWhel requires information regarding electrical efficiency. Differentiating between single cycle (SC) and combined cycle (CC) configurations, Figure 1 accounts for a range of efficiency values associated with state-of-the-art GT and RICE\(^10\). For RICE, even though the legislation does not distinguish between SC and CC, the two technologies are colored differently due to their different electrical efficiencies. The displayed data indicate that the more strict regulations (i.e., EU BAT conclusions, 13th BImSchV, an exemplary EPA permit for gas turbines) result in comparable emission limits in mass per generated energy output for SC-GT and SC-RICE. In contrast, the

\(^1\) ppmvd: parts per million by volume (dry)
\(^2\) For example, the German 13th BImSchV defines a reference oxygen content of 15 vol.% for GT and a reference oxygen content of 5 vol.% for RICE [3].
\(^4\) Best available techniques (BAT) conclusions for large combustion plants [4]
\(^5\) Directive on the limitation of emissions from certain pollutants into the air from medium combustion plants (EMCP) [6]
\(^6\) Verordnung über Großfeuerungs-, Gasturbinen- und Verbrennungsmotoranlagen (13. BImSchV) [3]
\(^7\) Verordnung über mittelgroße Feuerungs- Gasturbinen- und Verbrennungsmotoranlagen (44. BImSchV) [7]
\(^8\) Exemplary Environmental Protection Agency (EPA) site permit [8]
\(^9\) The EU BAT conclusions specify value ranges instead of fixed emission limits. Therefore, Figure 1 considers the upper and lower bound of the respective NO\(_X\) value ranges (BAT low and high).
\(^10\) For a given emission limit defined in ppmvd or mg/m\(^3\), an increase in electrical efficiency results in a decreased value in g/kWhel. Above certain efficiency thresholds for SC- and CC-GT configurations, the 13th BImSchV and the EU BAT conclusions stipulate a linear increase in emission limits depending on the electrical efficiency. As a result, Figure 1 and Figure 2 show constant emission limits when these efficiency limits are surpassed.
emission limits for CC-GT configurations imposed by the 13th BImSchV, the EU BAT conclusions, and the EPA permit stand out much stricter than RICE. This threshold is more relative deviation from the RICE limit value is assumed. The respective emission limits for both technologies with - for SC-GT, there are also widely differing limit values for both technologies with- in a regulation. For example, a significant deviation is found in the limit value given by the World Bank. This threshold is more than three times higher for RICE than for RICE and SC-GT imposed by 13th BImSchV, the EU BAT conclusions, and the EPA permit stand out much stricter than RICE’s emission limits. This indicates that current major regulations of NOx emissions are not fully technology-neutral and place a higher burden on operators of CC-GT power plants. However, while RICE must fulfill the 13th BImSchV emission limits for all operable loads, the limits for GTs apply only for loads higher than 70% of the nominal load. All emission limits below this load threshold are to be negotiated with the local authority [3]. The implications of these specifics for actual plant emissions will be briefly discussed in section 5.1. Equivalent to Figure 1, Figure 2 shows an apples-to-apples comparison between major carbon monoxide (CO) emissions regulations. The displayed overlap of the areas corresponding to GT and RICE configurations indicates similar emission limits for both technologies according to 13th and 44th BImSchV and can be stated as technologynutral. However, some regulations (i.e., EPA permit and EU BAT conclusions (low & high)) result in lower emission limits for GT compared to RICE. For a better comparison, the limit values for plants currently in operation are analyzed and listed in Table 1. For this purpose, a mean electric efficiency for each technology is assumed. The respective emission limits are given in mass per energy output and the relative deviation from the RICE limit value as a reference. Besides the broadly similar NOx limit values for RICE and SC-GT imposed by 13th BImSchV, BAT low, and an exemplary EPA permit (for SC-GT), there are also widely differing limit values for both technologies within a regulation. For example, a significant deviation is found in the limit value given by the World Bank. This threshold is more than three times higher for RICE than for SC- and CC-GT and therefore is of the scale of Figure 1. In contrast, the limit value imposed by the 44th BImSchV result in higher NOx emissions for SC-GT compared to RICE.

<table>
<thead>
<tr>
<th>Regulation</th>
<th>NOx emission limit [mg/kWh el]</th>
<th>CO emission limit [mg/kWh el]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC-GT (Ref.)</td>
<td>CC-GT (Ref.)</td>
</tr>
<tr>
<td>13th BImSchV</td>
<td>231 (-8%)</td>
<td>250</td>
</tr>
<tr>
<td>44th BImSchV</td>
<td>384 (+54%)</td>
<td>250</td>
</tr>
<tr>
<td>BAT low</td>
<td>115 (-14%)</td>
<td>133</td>
</tr>
<tr>
<td>BAT high</td>
<td>269 (-46%)</td>
<td>500</td>
</tr>
<tr>
<td>EMCP</td>
<td>384 (-39%)</td>
<td>633</td>
</tr>
<tr>
<td>EPA (exemplary)</td>
<td>237 (-65%)</td>
<td>671</td>
</tr>
<tr>
<td>World Bank</td>
<td>395 (-70%)</td>
<td>1331</td>
</tr>
<tr>
<td>El. Efficiency (%)</td>
<td>39</td>
<td>45</td>
</tr>
</tbody>
</table>

2 Modelling of actual engine and gas turbine emissions

While regulations define binding constraints for the operation of gas-based power generation technologies, a comprehensive emission footprint analysis must account for the real emission behavior considering a variety of power plant configurations and operating regimes. The following sections aim to present the methodology applied in the present study to model real emission behavior. To represent the operating characteristics of current RICE and GT, publicly available data were collected and used to derive load-dependent emission characteristics. Field measurements, testbed data, and manufacturer publications were considered for this approach. The data and methods are shown in the following sections.

Tab. 2. Overview of formation processes of considered species in gas-based power generation technologies.

<table>
<thead>
<tr>
<th>Species</th>
<th>Favorable conditions</th>
<th>Formation in RICE</th>
<th>Formation in GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>– High temperature – Sufficient oxygen excess</td>
<td>– fuel-rich, hot combustion inside the pre-chamber can result in NOx formation</td>
<td>– At higher loads due to high flame temperature</td>
</tr>
<tr>
<td>CO</td>
<td>– Incomplete combustion – Flame extinction</td>
<td>– flame quenching from unburned hydrocarbons (UHC)</td>
<td>– relatively low at higher loads due to complete combustion</td>
</tr>
<tr>
<td>UHC</td>
<td>– Incomplete combustion – Flame extinction</td>
<td>– flame quenching mainly in close-wall regions and cavities</td>
<td>– Increasing formation with load reduction operation</td>
</tr>
<tr>
<td>HCHO</td>
<td>– intermediate species during fuel oxidation – Complete combustion</td>
<td>– The quenching distance increases for leaner mixtures and lower temperatures.</td>
<td>– Very high at ignition and startups</td>
</tr>
<tr>
<td>PM</td>
<td>– Fuel-rich zones – High temperatures – As there is no C-C bond in CH4, PM emissions derived from CH4 combustion are very low</td>
<td>– mainly from the pre-chamber – PM (and SOx emissions may occur due to combustion of lubricating oil (consumption ~0.4 g/ kWhel for modern gas engines)</td>
<td>– as for CO, formation increases at lower part-loads compared to CO</td>
</tr>
</tbody>
</table>

2.1 Pollutant formation in RICE and GT

Before discussing the real emission data, a brief overview of the fundamental formation processes of the relevant pollutants are described in Table 2.
2.2 Emissions of RICE

To model the emission behavior of RICE, publicly available datasets were used. The following considerations focus mainly on CH\textsubscript{4} and NO\textsubscript{X} since gas engines historically have an oxidation catalyst (OC) for CO and formaldehyde (HCHO) suppression (e.g., in Germany, at least if TA-Luft 2002 was applicable). Therefore, field measurements of these components are rare, and it is often not clearly stated whether a catalyst was used. This study focuses on medium-speed engines (engine speed <1200 1/min, bore diameter ≥200 mm). Since many of the available datasets do not exactly specify the engine for reasons of confidentiality, the datasets were assigned to likely engine types. Hence, the bore diameters depicted in the following have some uncertainty. With this approach, a sufficient significance of data for the desired engines could be achieved, and effects of the engine calibration and of the displacement can be distinguished.

Figure 3 summarizes mainly full load CH\textsubscript{4} and NO\textsubscript{X} emissions for different bore diameters. Both pre-chamber gas engines (LBSI) and dual-fuel gas engines (LPDF) are depicted. The figure includes both engines for maritime propulsion and combined heat and power applications. The same is true for Figure 4 and Figure 5. Therefore, some values are normalized by the electrical and some by the mechanical power adding an uncertainty in the range of the losses by the generator (usually <3% for medium-speed engines).

On average, CH\textsubscript{4} emissions decrease with increasing bore diameter regardless of the technology. The improved surface-to-volume ratio reduces quenching in the combustion chamber. Moreover, the volume in the piston top land is smaller in relation to the displacement. Usually, combustion stability is also improved at the same air-to-fuel ratio (AFR) partially due to the lower engine speed (flame kernel development).

A second evident trend is that pre-chamber gas engines have lower CH\textsubscript{4} emissions compared to dual-fuel gas engines. This is because the turbulence from the jet ignition fastens the burn and makes it more complete. For the same reason, the NO\textsubscript{X} emissions are usually reduced with increasing bore diameter since leaner AFRs are stable for larger bore diameters. Besides the worsened CH\textsubscript{4} emissions for the dual-fuel gas engines, also the NO\textsubscript{X} emissions are increased since the pilot diesel injection usually produces higher NO\textsubscript{X} emissions compared to a pre-chamber.

As the graph in the upper right corner depicts, there is a tradeoff between CH\textsubscript{4} and NO\textsubscript{X} emissions. Richer operation reduces the quenching distance and hence CH\textsubscript{4} emissions but favors NO\textsubscript{X} formation due to higher peak combustion temperatures. Later combustion phasing, on the other hand, reduces peak combustion temperatures and hence NO\textsubscript{X} formation, but temperatures during expansion are also lower, resulting in increased flame quenching and hence CH\textsubscript{4} emissions.

While the first dual-fuel gas engines had substantial CH\textsubscript{4} emissions, current medium-speed gas engines with bore diameters >300 mm can be expected to have CH\textsubscript{4} emissions in the range stretched by the newly imposed 13\textsuperscript{th} BlmSchV level (900 mg/m\textsuperscript{3} total carbon @ 5%, i.e., ~2.8 g/kWh\textsubscript{el} when 47% efficiency assumed) and 2 g/kWh\textsubscript{el} while dual-fuel gas engines should be in the range of 3.5 g/kWh\textsubscript{el}. That said, a recent press release by Wärtsilä [33] reports full load CH\textsubscript{4} emissions in the range of 1 g/kWh\textsubscript{el} for the latest engines. Hence, significant efforts have been focused on reducing the methane slip in recent years. While one reason for this reduction surely is the increasing interest in the climate gas methane, which can result in significant CO\textsubscript{2}-eq. emissions even while using CO\textsubscript{2}-neutral bio-methane, a more pragmatic reason is to minimize the fuel slip to improve efficiency. The measures for these improvements will be discussed in more detail for the load-dependent CH\textsubscript{4} emissions.

NO\textsubscript{X} emissions have been in the range of ~1.2 g/kWh\textsubscript{el} (TA-Luft 2002) for many years to avoid NO\textsubscript{X} after treatment. However, the new limit in the 13\textsuperscript{th} BlmSchV is not manageable without significant losses in efficiency. Therefore, a selective catalytic reaction (SCR) will become mandatory in the future for gas and dual-fuel gas engines. JRC [4] and EPA [14] plant data suggest NO\textsubscript{X} emission levels with SCR catalyst below 0.1 g/kWh\textsubscript{el} with more than 90% conversion rates. The tradeoff between CH\textsubscript{4} and NO\textsubscript{X} emissions can then also be used to improve CH\textsubscript{4} emissions with the SCR by calibrating a richer AFR or earlier combustion phasing. However, significant gains in efficiency are not expected for gas engines since calibration at TA-Luft 2002 emissions is usually possible with settings close to the best efficiency calibration.

Figure 4 shows load-dependent CH\textsubscript{4} and NO\textsubscript{X} emissions. In general, CH\textsubscript{4} emissions...
increase with reducing load. The reduced temperature level leads to an increased quenching layer thickness. Many results are influenced by improper AFR control, though. To distinguish the influences, these will be discussed in the following based on the excellent summary by Krivopolianskii [35]. The simplest measure is to avoid fuel slip during the gas exchange. All modern engines no longer have this problem. AFR control can significantly improve CH4 emissions. Especially older DF engines often did not have any control mechanism for the turbocharger. Moreover, the marine engines depicted are significantly overturned for NOX emissions since the International Maritime Organization (IMO) does not specify an emissions limit of ~ 2.4 g/kWh depending on the engine speed. This leads to significantly leaner operation at low load, where richer operation would be required for similar combustion efficiencies. Possibilities in this regard are blowoff-values (BOV), throttle valves, and waste gates or a variable turbine geometry (VTG) turbocharger. In addition, higher charge air temperatures reduce the quenching layer thickness, but increase NOX emissions and may lead to derating depending on the methane number of the gas.

Moreover, cavities in the combustion chamber should be reduced. Emissions from cavities increase with richer AFR and can therefore not be reduced with measures that shift the operation to lower CH4 emissions at increased NOX emissions. Furthermore, the piston bowl can be optimized for the surface-to-volume ratio to minimize wall quenching. This optimization cannot be conveyed to dual-fuel engines to the same degree due to operation in diesel mode.

As most modern engines consider these optimization measures, the solid curves (black: LBSI, dark red: LPDF) were derived from the data presented for modeling. Due to a lack of data for loads below 10%, emission and fuel mass flows are modeled to be constantly the value at 10% load as a conservative estimate. According to data presented by Baas [36], the light-off should be reached within 20 to 30 min after startup. This time will vary depending on the detailed design of the exhaust system.

Finally, Figure 5 summarizes the PM, formaldehyde, and CO emissions. To reach the 13th BImSchV CO emission limit, an OC is required. CO has a relatively low light-off temperature, though. According to data presented by Baas [36], the light-off should be reached within ~3 min after startup but might vary depending on the detailed design of the exhaust system.

Similarly, the 13th BImSchV formaldehyde emission limit requires an OC. Light-off should be reached within ~5 min after starting due to a slightly higher light-off temperature compared to CO. Also, here the light-off might vary depending on the detailed design of the exhaust system.

13th BImSchV PM limits are not a major concern for gas operation, not even for dual-fuel gas engines. Specific PM emissions increase in low load situations (higher specific oil consumption and diesel share for dual-fuel gas engines). Still, the data analyzed for dual-fuel gas engines suggests that the limits are still met for part-load. However, operation in liquid fuel mode produces significantly higher PM emissions (~120 mg/kWh at high load).

For all these components, load-dependent emissions were rare in the literature. Still, CO and formaldehyde are considered to be load-dependent. For CO, a best guess based on experience was derived, while for formaldehyde, the load dependency of the methane emissions is used. This is a conservative estimate since formaldehyde from quenching should be like CO with a less severe rise at part load compared to CH4.

2.3 Emissions of gas turbines

In analogy to RICE, the GT part load emission characteristics were derived using the discussed emission formation processes in combination with publicly available data. While gas turbine manufacturers mainly provide full-load data for regulated emission species such as NOX and CO, information on (mostly) unregulated species (e.g., UHC, formaldehyde, PM) is lacking as they are typically not measured during operation. Moreover, data on part-load characteristics of the emission species with in the present study’s scope is scarce. Such information is dependent on the corresponding gas turbine; thus, manufacturer dependent and typically confidential. However, suitable data sets could be identified, allowing the derivation of a part-load characteristic for the main emission species, i.e., NOX, CO, and UHC, of state-of-the-art premixed-type (typically referred to as Dry-low-NOX (DLN)) gas turbine engines. As the primary source of raw information, the Environmental Protection Agency (EPA) database was used. Power plant operators in the USA are obliged to submit detailed information on their key-monitoring data to the EPA [14]. This data comprises hourly values for electrical power output, fuel consumption, and emissions of nearly all available power generation units in the USA. For the present study, the APMD (Air Markets Program Data) 2021 data set [14] was utilized. Suitable data sets were identified by applying appropriate filters to comply with the scope of the present study, e.g., single-cycle combustion turbines, nominal electrical power between 10-100 MW, natural gas-fired, and no designated emission control strategy. Five data sets comprising over 20,000 load points were extracted and used for further evaluation.

The expected NOX characteristics can be derived from the formation processes described in Table 2 and include the following features:

- NOX emissions slightly decrease during load reduction from full-load conditions due to the lower flame temperature of the pre-mixed DLN burner
- NOX emissions are roughly constant until the switch to diffusion-type pilot burner operation
- NOX emissions increase due to load transfer to the pilot burner
- NOX emissions are at their maximum if the pilot burner operates at its load maximum
- NOX emissions decrease with further load decrease due to lower flame temperature and load reduction of the pilot burner

Considering the expected NOX characteristics, the operation data was evaluated in more detail to account for different combustor operation modes, i.e., diffusion-type pilot operation at low loads and load-dependent switch to a pre-mixed DLN burner at a particular load point. Relative dependencies between different load points were derived from the data and combined with “ideal” NOX trend curves provided in the scientific literature [15] to derive a part-load characteristic for newly-built turbines. The load-dependent NOX emission characteristic is presented in Figure 6.
Fig. 6. Load-dependent GT NOx emissions in ppmvd.

An efficiency characteristic is needed to convert the full-load emission values to the selected apples-to-apples metric, i.e., mg/kWhel over the entire load range. The underlying efficiency characteristic used in the present study was derived by combining available information from gas turbine manufacturers [17] and scientific literature [18, 19].

As a result, the NOx emission part-load characteristic can be converted into the apples-to-apples metric. Figure 7 shows the exemplary results for a SC-GT with an emission level of 15 ppmvd @ 15 vol.% O2 and electrical efficiency of 39% at full load [20], which equals 236 mg/kWhel. It should be noted that Figure 7 depicts the emission behavior of the gas turbine over the entire load range, including load points below the minimum environmental load. At loads below the MEL, emissions are no longer in compliance with the legislation. Thus, operation over extended periods is not permissible at loads below the MEL.

While data on NOx emissions must be reported to the EPA, reporting of other pollutants such as CO or UHC emissions is not mandatory. Since no other turbine data source could be identified, a plausible part load CO & UHC emission characteristic was derived from the scientific literature [15, 21, 22]. The following trends are expected for CO:

- Rapid and exponential increase towards lower loads when diffusion-type pilot burners are activated for flame stabilization

The expected results were used to benchmark the derived CO part-load characteristics. For UHC the same trend as for CO emissions was assumed but shifted 10%-points towards the lower load in compliance with the underlying scientific literature [15, 21, 22]. The resulting trend curves parameterized for CO and UHC emissions are displayed in Figure 7. The corresponding full-load emission values are 19 mg/kWhel for CO (2 ppmvd @ 15 vol.% O2) and 33 mg/kWhel for UHC (TOC as C3H8; 2 ppmvd @ 15 vol.% O2) based on an electrical efficiency of 39%. Additionally, the 13th BImSchV emission limits are displayed corrected with the underlying part load efficiency characteristic of a SC-GT.

For the present study, a somewhat optimistic starting point (at 20% relative load) for the CO emission increase was chosen to represent state-of-the-art gas turbines and comply with the underlying scientific literature. However, it should be mentioned that the individual starting point varies manufacturer- and engine-dependent. For formaldehyde and PM emissions, load-dependent part-load characteristics could not be found in the publicly available literature. Primarily, investigations on formaldehyde emissions from gas turbine engines are very scarce. This may be attributed to formaldehyde emissions being typically very low [21], although they account for the highest share of hazardous air pollutants (HAP) [23]. Formaldehyde forms as an early intermittent species of methane oxidation [24]. Thus, very low formaldehyde emissions are expected under complete combustion conditions, although a similar trend to CO can be anticipated towards very low loads [25]. However, no detailed information on the formation process of formaldehyde for reduced loads was found in the available literature. As a result, for the present study, formaldehyde emissions were accounted for by a constant value over the entire load range (3 mg/m3 [23], i.e., 23 mg/kWhel for an electrical efficiency of 39%). Since the available literature data is not sufficient to model PM with satisfactory accuracy, an averaged value over the entire load range was assumed (1 mg/m3 [26], i.e., 8 mg/kWhel for an electrical efficiency of 39%). This should be a conservative estimate since PM emissions from gas turbines are generally very low [27]. The corresponding part load trend curves for both PM and HCHO emissions are subsequently derived by the application of the part-load efficiency characteristic of a SC-GT.

3 Modeling approach for the gas-based power plants

This section explains the underlying modeling approach for aggregating individual RICE or GTs into a power plant configuration, the plant operation for a given load profile, and the corresponding emission calculation. For this purpose, an EXCEL-based model framework was developed.

To highlight the different modes of operation of gas-based power generation plants, an exemplary “peaking” scenario and an exemplary “baseload” scenario are examined in detail. The two scenarios differ in power plant configuration. The peaking scenario comprises plant configurations that feature multiple and rapid startups and shutdowns as well as transient operations. Therefore, one SC-GT and the corresponding number of about 10 MWel RICE to reach the same power output represent the plant configuration of the peaking scenario. In contrast, the baseload scenario features plant configurations that focus on efficient power generation close to full-load operation. Consequently, a CC-GT and the corresponding number of about 20 MWel RICE to reach the same power output represent the plant configuration of the baseload scenario. The corresponding load profiles used for each scenario are derived from publicly available actual plant operation profiles of a CC-GT power plant located in Germany [37]. Since the real load profile of an aggregated RICE power plant may exceed the transient capabilities of conventional GTs, a load profile was chosen that both technologies can be operated with. In the case of high tran-
efficiency in %

Fig. 8. Part-load characteristic of plant configuration shown as peaking configuration.

However, the efficiency mode is more appropriate for a direct comparison to a gas turbine power plant with, in this comparison, lower transient capabilities.

In the following, the modelling approach is exemplarily described for the peaking scenario since the dynamic operation of the gas-based power plants as a backup for renewable power generation will gain importance in the future. Figure 8 presents the part-load characteristics of the aggregated plant configurations comprising electrical efficiency and emissions. As the nominal plant load is set to the nominal power of the gas turbine, the trends for the SC-GT plant configuration follow the trends of the individual machine, presented in section 3.3. Due to the need for engine aggregation for the RICE power plant to cover the desired plant load, both deployment strategies are displayed, and the efficiency and emission advantage are detectable, while the spinning mode represents the behaviour of a virtual single-engine. For the RICE configurations,

sient load profiles, a different GT technology, e.g., aero derivatives, could be selected but was not considered in the present study. Detailed load profiles for two-week operation were extracted and scaled from the actual plants’ nominal power to the nominal power of the desired scenario plant configuration. While daily startups and a load reduction around noon characterize the load profile of the peaking scenario, the baseload scenarios load profile features one startup every two weeks and otherwise operation close to full load.

The main characteristics of the investigated operation scenarios are listed in Table 3. The same electrical plant power and load profile are used for each scenario’s GT and RICE configurations. In addition, the load profile characteristics were extrapolated to a full-year virtual operation, although two weeks were actually calculated.

Finally, two alternative strategies are considered to examine the plant operator’s engine deployment when engine aggregation is necessary to cover the required plant load. While in “efficiency mode”, there is only one engine operating in part-load, and the remaining active engines are operated in full-load, in “spinning mode”, the plant load is equally distributed to all engines. Thus, the minimum and the maximum number of active engines covering the plant load are represented. Furthermore, since the engines operate at the same load point in “spinning mode”, the plant’s efficiency and emission curves follow a virtual single engine with the same nominal load as the power plant. In “efficiency mode”, however, only one engine is operated in part-load, while the other engines are either operated in full-load or are shut down. Therefore, an efficiency advantage can be achieved compared to the “spinning mode”, while the “spinning mode” guarantees a faster response to additional load demands as all engines are in operation at all plant loads. Thus, “spinning mode” operation makes sense for grid stabilization and for the highest load ramping requirements or in the case of off-grid operation when high availability of power is required.

Tab. 3. Scenario overview and full-load emission values for plant configuration.

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Peaking Scenario</th>
<th>Baseload-Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Configuration</td>
<td>Nr. of aggregates (&amp; type)</td>
<td>1 x SC</td>
<td>6 x 1 CC</td>
</tr>
<tr>
<td></td>
<td>$P_{el,engine}$ [MW]</td>
<td>57</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>$\eta_{el}$ [%]</td>
<td>39.1</td>
<td>47.4</td>
</tr>
<tr>
<td>Full-load Emissions</td>
<td>CO$<em>2$ [g/kWh$</em>{el}$]</td>
<td>505</td>
<td>417</td>
</tr>
<tr>
<td></td>
<td>CH$<em>4$ [mg/kWh$</em>{el}$]</td>
<td>33</td>
<td>2400</td>
</tr>
<tr>
<td></td>
<td>NO$<em>x$ [mg/kWh$</em>{el}$]</td>
<td>236 (24*)</td>
<td>1400 (140*)</td>
</tr>
<tr>
<td></td>
<td>CO [mg/kWh$_{el}$]</td>
<td>19</td>
<td>1200 (120*)</td>
</tr>
<tr>
<td></td>
<td>HCHO [mg/kWh$_{el}$]</td>
<td>23</td>
<td>90 (9*)</td>
</tr>
<tr>
<td></td>
<td>PM [mg/kWh$_{el}$]</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Load Profile</td>
<td>Equivalent full-load hours [h]</td>
<td>3735</td>
<td>6003</td>
</tr>
<tr>
<td></td>
<td>Number of plant starts per year</td>
<td>286</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Av. plant load in operation [%]</td>
<td>81</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Actual operating hours per start</td>
<td>16</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>Year &amp; Calendar week</td>
<td>2020, 40 &amp; 41</td>
<td>2020, 3 &amp; 4</td>
</tr>
</tbody>
</table>

*: with emissions after treatment (EAT) with an assumed constant 90% conversion efficiency

12 2x1 CC-GT: The plant configuration consists of two gas turbines and one steam turbine

* Contraction efficiency of 90% assumed

Without EAT

With EAT

Conversion efficiency of 90% assumed

With EAT

Conversion efficiency of 90% assumed

Without EAT

Conversion efficiency of 90% assumed

With EAT

Conversion efficiency of 90% assumed

Without EAT

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Conversion efficiency of 90% assumed

With EAT

Conversion efficiency of 90% assumed

Without EAT

Conversion efficiency of 90% assumed
not taken into account. However, the constant conversion efficiency is assumed to 90%, although, typically the conversion efficiency of state-of-the-art EATs can be higher at stationary, i.e., warmed up, operating conditions. This thesis is supported by data from Baas [36] and plant NOx emission levels with SCR catalyst below 0.1 g/kWh el published by JRC [4] and EPA [14].

For the calculation of the individual power plant's operation point, each load profile is analyzed minute-wise according to the following rules:

- Calculation of the plant operation point by matching the required plant load given by the load profile with the plant configuration's efficiency and emission characteristic.
- In efficiency mode, additional engines are started if the required load gradient exceeds the possible load gradient of the active engines required to cover the load.
- Plant loads below 10% are not considered (minimum plant load).
- The idle operation of an engine is calculated using emission values at the minimum plant load point.
- A transient penalty of +10% of the current emission value is added to account for transient load changes.
- A startup penalty is added to consider emissions during engine ignition and acceleration before synchronization. The startup penalty is calculated using the emission values at a defined minimum engine/gas turbine load point.
- An engine is shut down when it is not required for the next five minutes.

The results of the minute-wise plant operation in the SC/Peaking scenario are shown in Figure 9. As the GT and RICE configurations feature the same nominal load, all configurations' load profiles and electricity outputs are the same. The difference between both RICE deployment strategies can be seen in the number of required engines. In "spinning mode", all six engines are operated with the same load in parallel. In contrast, in "efficiency mode", the engines are operated sequentially. Due to the higher electrical efficiency of the RICE, the cumulative fuel consumption is less than that of the GT configuration to generate the same electrical energy.

In Figure 9, the time-dependent CH4 emission generation is exemplarily shown, while the time-integrated cumulative curves for the other emissions species are shown. The plant is modelled as idle during plant shutdown periods for calculation stability since the plant load is below the minimum load threshold. However, the emissions produced during idle are not added to the final results, which can be seen in the curve for the cumulative CH4 emissions. In addition, since EAT systems are installed as standard in engine power plants to comply with emission regulations, the cumulative emission values of the species NOx, CO, and HCHO are also given after EAT for the RICE configurations.

4 Comparative analysis of different gas-based power generation technologies regarding their environmental footprint

This section incorporates the emission calculation results of the investigated plant configurations and operation modes as well as a subsequent environmental impact analysis.

4.1 Comparative analysis of emission values

Figure 10 (CO2, CH4, NOx) and Figure 11 (CO, HCHO, PM) show the results for the considered emission species for both scenarios, i.e., peaking/SC and baseload/CC operation for the GT and RICE power plant configurations. Both figures distinguish between the black-framed full-load emission value and the green-framed additional emissions due to startup, transients, and part-load operation. In addition, the respective emission limit imposed by the German 13th BImSchV is indicated in the orange boxes. However, in contrast to section 2.2, the limit values shown were calculated using the plant's average electrical efficiency during operation in the corresponding scenario. The height of the stacked bar represents the overall emissions in the apples-to-apples metric, i.e., mass per generated kWh el. As the plant configurations of each scenario are calculated with the same load profile, the bars also show the differences in the total emissions for GT and RICE in the same scenario.

As the CO2 plots in Figure 10 indicate, the carbon dioxide emissions are significantly influenced by the electrical efficiency of the plant configuration. Thus, the CC-GT plant configuration can achieve the lowest CO2 emissions across all configurations due to the highest efficiency. Due to the higher single cycle efficiency over the entire load range for the RICE compared to the SC-GT (see Figure 8) the RICE produces lower CO2 emissions. Additionally, as there is no relevant efficiency loss for the RICE configurations over a wide load range when oper-
In the peaking scenario, the NO\textsubscript{x} emissions of the GT configuration exceed the RICE configurations’ emissions. This can be attributed to the EAT, which is only considered for RICE power plants in the form of an OC (for CO and HCHO) and SCR (NO\textsubscript{x}) with an averaged, constant conversion efficiency since the raw emissions are typically an order of magnitude greater than the emission values with EAT. However, while the difference is significant in the peaking scenario, emissions are comparable for both technologies in the baseload scenario. Additionally, the transient operation does not significantly affect the emission values for both RICE configurations. The SC-GT’s startup and part-load emission characteristics considerably influence the total emissions in both scenarios. In the peaking scenario, the high NO\textsubscript{x} emissions at lower partial load and startup operation attributable to the pilot burner (see Figure 7) cause a visible deviation from the full-load emissions. On the other hand, in the baseload scenario, the slight dip in NO\textsubscript{x} emission at a very high part-load (see Figure 7) is responsible for reduced specific emissions compared to full-load.

Both RICE configurations in peaking operation are clearly below the NO\textsubscript{x} limit value of the 13\textsuperscript{th} BImSchV with EAT system, although higher values are likely to be observed during the warmup of the EAT. However, these elevated emission levels during operation with lowered EAT efficiency are accounted for by half-hourly averages in the 13\textsuperscript{th} BImSchV. The half-hourly emission averages are twice as high as the shown hourly mean value. A slight exceedance can be observed for the SC-GT; however, the shown limit value can solely serve as an indicator since the 13\textsuperscript{th} BImSchV limit for GTs only applies to loads above 70\% of the nominal power. As the shown emission results consider the entire load range and include transient processes, the presented value is not directly comparable with the limit value given by the 13\textsuperscript{th} BImSchV. However, the full-load emission value for the SC-GT is already within the limit value range. Therefore, considering only the load range above 70\%, compliance with the limit value is already technologically challenging. For the baseload configurations, the comparison between the limit values implied by the 13\textsuperscript{th} BImSchV shows the significantly stricter regulation of CO-GT emissions compared to RICE, see Figure 1 and section 2.2. As a result, the CC-GT substantially exceeds the limit despite comparable absolute emissions with RICE, while the emissions produced by RICE stay well below their limit value. The CC-GT limit implied by the 13\textsuperscript{th} BImSchV can only be met using an exhaust gas after-treatment (i.e., SCR). If this additional equipment is applied, the CC-GT emissions are significantly below the limit value as well as the emissions of the RICE configuration, which uses exhaust gas treatment in any case.

In the peaking scenario, the SC-RICE configurations produce higher emission values for CO compared to the SC-GT configuration. However, while the SC-RICE emissions at the nominal load essentially define the absolute emissions, the SC-GT emissions are mainly driven by startup, transient and part-load operation. Due to many startup processes and the associated operation at low load points, the SC-GT emissions increase significantly compared to the full-load emissions in the peaking scenario. In contrast, in the baseload scenario, the CO emissions of the CC-GT configuration are considerably lower, and negligible deviation from the full-load value is visible. This is because the load profile predominantly provides operation in the upper load range and just a single plant start every two weeks.

Despite the apparent differences between scenarios and technologies, the CO limit values of the 13\textsuperscript{th} BImSchV are complied with in all considered cases. For the RICE configurations, however, this requires an OC.

---

**Fig. 10.** Emission results for CO\textsubscript{2}, CH\textsubscript{4}, and NO\textsubscript{x} for both scenarios (above: Peaking; below: Baseload).

**Fig. 11.** Emission results for CO, HCHO, and PM for both scenarios (above: Peaking; below: Baseload).
The PM emissions produced by RICE are typically well above those associated with GT operation. This can be mainly attributed to the different combustion principles. However, both technologies’ emissions are at a low level. The displayed limit value is derived from liquid fuels since for methane as fuel, no PM limit value is given in the 13th BImSchV. In the case of HCHO emissions, a relevant difference between RICE and GT is apparent. This finding can be attributed to the fact that the OC for RICE significantly reduces HCHO emissions. However, both GT and RICE comply with the limit values of the 13th BImSchV.

### 4.2 Environmental Impact Analysis

Based on the respective specific emission values of the species considered, the environmental impact can now be quantified as a final step of this study. Unfortunately, there is no uniform metric for determining the environmental footprint as a single score. Instead, relevant literature suggests various damage pathways and impact categories with strongly varying confidence levels, see for example the JRC recommendations of the European Commission on Life Cycle Impact Analyses [40]. Furthermore, even for a specific environmental damage pathway, the metrics and their characterization factors vary greatly for the individual species. Therefore, in this study, two parameters are chosen so that all species under consideration appear at least once. Firstly, the Global Warming Potential (GWP) is analyzed to represent the effect of greenhouse gas emissions. The second parameter represents the damage caused by air pollutants, i.e., the Human Toxicity Potential (HTP). Since the difference in the emission results for both operation strategies (“efficiency mode” and “spinning mode”) of the RICE configurations in the peaking scenario is negligible, only the “efficiency mode” results are displayed in the following section.

To quantify the emissions’ impact on global warming, the GWP is used to calculate CO2 equivalents per kWh. The GWP metric relates the effect of a radiation absorbing gas in the atmosphere to CO2 molecules of an equal mass. The GWP considers the time-integrated radiative forcing (RF), which represents the cumulative change in the radiation balance of the earth and atmosphere system of the considered species. As CO2 has a long atmospheric lifetime, the time-integrated RF increases for centuries. In contrast, the other major GHG considered in the present study (CH4) has a short atmospheric lifetime. Therefore, the time-integrated RF stays constant after about 50 years because the CH4 has almost been degraded and no longer causes RF [38]. Hence, the calculation of the GWP depends on the respective time horizon. For a short-lived gas like CH4, the GWP declines with an increasing time horizon. Thus, the time horizon for evaluating the GWP metric depends on many factors and considerations: On the one hand, it is necessary to consider the short-term climate impact of short-lived gases. On the other hand, their contribution to global warming should not be overestimated in the long turn, possibly resulting in wrong incentives for emission reduction measures [39]. Therefore, the commonly used GWP100 (CH4 = 28 [38]) and the GWP20 (CH4 = 84 [38]) are presented in Figure 12 to quantify the short- and medium-term impact on climate change of the results shown in section 5.1.

When CO2 emissions and CO2-equivalents of the CH4 emissions are accumulated, the RICE’s efficiency advantage compared to the SC-GT is mostly compensated. Therefore, under consideration of the GWP100, the SC configurations have comparable emissions. However, considering the GWP20 results in higher RICE emissions than the SC-GT due to the increased characterization factor of CH4 considering the shorter time horizon. On the other hand, the GTs emissions are well below the RICE emissions for CC configurations. This is because the CC-GT’s electrical efficiency is higher than the efficiency of the RICE, and there are no relevant CH4 emissions for GTs (see Figure 11).

In addition to the climate impact, the Human Toxicity Potential was analyzed to consider local pollutants. In Table 4, the characterization factors for the different species are shown in Toluene equivalents. In this rating, the HCHO emissions are quantified as the most dangerous of the considered species in terms of human toxicity. Moreover, in [41], a characterization factor for ammonia of 7.5 is given as well. At this point, it should be mentioned that ammonia is required for the operation of the SCR catalytic converter and, depending on the necessary NOX reduction rate and consequently the amount of ammonia used, ammonia emissions can occur, which then also has an environmental impact. However, the available data on ammonia emission is limited; therefore, this effect cannot be illustrated at this point of the study.

The results of the HTP calculation are shown in Figure 13. The figure illustrates that the HTP results are mainly driven by the quantity of HCHO and NOX emissions. Although NOX emissions do not have the strongest toxic effect, their impact on the HTP results is predominant due to the high-

---

**Fig. 12. Environmental impact comparison as Global Warming Potential (Characterization Factors from [38]).**

**Fig. 13. Environmental impact comparison as Human Toxicity Potential.**

---

**Tab. 4. Characterization Factors for Human Toxicity Potential [41].**

<table>
<thead>
<tr>
<th>Species</th>
<th>CO</th>
<th>NOX</th>
<th>HCHO</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg Toluene-eq / kg</td>
<td>0.27</td>
<td>4.3</td>
<td>16</td>
<td>2.9</td>
</tr>
</tbody>
</table>

---

The table above shows the characterization factors for human toxicity potential using Toluene equivalents for different species. CO, NOX, HCHO, and PM10 are the species considered, with their respective characterization factors indicated in kg Toluene-eq/kg.
The results of the HTP calculation are shown in Figure 10 and Figure 11. However, because of the small characterization factor of CO and the relatively low PM emissions of both considered technologies, these two species do not impact the HTP significantly. Therefore, this effect cannot be illustrated at this point of the study.

The results of the HTP calculation are shown in Figure 13. The figure illustrates that the HTP results are mainly driven by the quantity of HCHO and NOX emissions. Although NOX emissions do not have the strongest toxic effect, their impact on the HTP results is predominant due to the higher quantity of NOX emissions compared to the other species under investigation (see Figure 10 and Figure 11). However, because of the small characterization factor of CO and the relatively low PM emissions of both considered technologies, these two species do not impact the HTP significantly.

As the GT’s specific NOX and HCHO emissions are higher than the correspondent RICE configuration’s emissions, the GTs HTP exceeds the value for RICE in both scenarios. However, only the SC-GT stands out in this comparison, while for RICE and the CC-GT configurations, comparable values for the HTP can be observed. This is due to the higher electrical efficiency of the CC-GT, which compensates for the higher specific emissions of the other species. Moreover, when EAT is applied to GT power plants, their HTP impact is significantly reduced.

5 Summary and outlook

In this study, gas-based power generation technologies, i.e., RICE and GT, were investigated with regard to their emission behavior and corresponding regulations. As regulations and scientific publications commonly employ different units and reference oxygen contents in the exhaust for quantifying emissions from GT and RICE, i.e., ppmv or mg/Nm³, a direct comparison between technologies is typically not possible. To overcome this limitation, the present study presents the emissions in an apples-to-apples metric, i.e., mg/kWhₜₐ₉. Subsequently, the major regulations for NOX and CO emissions were analyzed and compared in the apples-to-apples metric. Converted to mg/kWhₜₐ₉, it becomes visible that the stricter regulatory frameworks (EU BAT conclusions, 13th BImSchV, EPA) result in comparable NOX emission limits for SC-GT and SC-RICE, while the limits for CC-GT are much stricter compared to the CC-RICE limits. Regarding CO emissions, the emission limits can be reduced by the technological factor neutral with a few exceptions, e.g., exemplary EPA permits and EU BAT conclusions.

To investigate the emission behavior of the two technologies for different power plant configurations and operation regimes, this study introduces a modeling approach for the emission calculation of GT and RICE power plants. In a first step, the part-load behavior of the electric efficiency and the most important emission species were derived from publicly available data. In a second step, the single GT or RICE models were aggregated to a power plant configuration using an EXCEL-based model environment. While a single-cycle GT and the corresponding number of 10-MWₑₙ₉ RICE were considered in a “peaking” scenario, a combined-cycle GT and the corresponding number of 20-MWₑₙ₉ RICE were considered in a “base-load” scenario. In addition to the emission behavior during part-load operation, the ignition and startup phase, as well as any additional penalty for the transient operation were considered. Since exhaust gas after-treatment systems (SCR and OC) in RICE plants are commonly applied, both were included for the calculation of RICE with a constant conversion efficiency of 90.5%. For the GT, however, no EAT was considered. Finally, the major emission species were calculated for both technologies in two operational scenarios, i.e., peaking and base-load operation. Based on the comparison of the technologies, the apples-to-apples metric of mg/kWhₜₐ₉ was used again.

The plant performance for each operating scenario was calculated leveraging a load profile derived from real plant data. Due to frequent load changes and startup processes, the emission results indicate that peaking operation can result in higher average emission values in comparison to the full-load value associated with the related technology. This finding is especially evident in the CO emission results of the GT, as CO increases drastically at partial load. For the remaining emission species considered in the present study, the part load emission value does not increase as significantly as for CO emissions. Therefore, the influence of the operating regime on the results of the remaining emission species is negligible. However, RICE requires EAT for NOX (SCR), CO, and HCHO (both OC) to comply with strict emission limits, e.g., the German regulation 13th BImSchV. To comply with the stricter NOX limit, the CC-GT must also be equipped with EAT. Since SC-GT currently in operation are typically not equipped with EAT, they will significantly exceed the stricter emission limits despite comparable absolute emissions with RICE. In SC operation, NOX emissions of GT surpass the corresponding RICE emissions. However, SC-GT NOX emissions are within the limit value implied by strict emission legislation, e.g., 13th BImSchV. The calculated CO emissions show that GTs have lower emissions than RICE in both scenarios. The 13th BImSchV limit value is complied with by a wide margin by all the configurations considered.

Finally, the emission data for each species were examined regarding their environmental impact. The Global Warming Potential (GWP) and the Human Toxicity Potential (HTP) were applied as comparative indicators. As the efficiency drives the CO₂ emissions, the CC-GT has the lowest impact on climate change of the considered technologies. This finding is further backed by the fact that there are no significant CH₄ emissions during gas turbine operation. The efficiency advantage of the SC-RICE compared to the SC-GT is partly (using the GWP₂₀) or fully (using the GWP₉₅) compensated by the CO₂-equivalent emissions of the RICE’s CH₄ emissions. Regarding the HTP, the emission species with the highest impacts are NOX and HCHO. As the GT configurations have higher NOX and HCHO emissions in both scenarios, the impact on Human Toxicity is higher in comparison to the RICE configurations commonly built with EAT. While the CC-GT without EAT has a comparable HTP to both RICE configurations, the SC-GT stands out with the highest HTP in this comparison. However, EAT with an average conversion rate of 90% under all operating conditions is necessary for the RICE to achieve the calculated HTP.

The methodology applied in the present study employs a holistic comparison between two technologies with the same inputs and outputs on an apples-to-apples basis. Moreover, the present study does not solely focus on thermodynamic performance but also leverages a detailed analysis of the emissions associated with the electricity supply through both technologies. Going a step further, the emissions are aggregated into different damage pathways and impact categories which summarize the environmental impact of other emissions species. In such a way, a comprehensive thermodynamic and ecologic analysis of both technologies in different operating scenarios is allowed. In further studies, the methodology can be improved by using more detailed transient and part-load characteristics for the emissions of the considered GT and RICE. Moreover, full-load emission values of new state-of-the-art engines and "engines in operation" need to be distinguished. Additionally, the heat-up phase and degradation of the EAT systems should also be modelled to account for the conversion efficiency of the catalysts more precisely during plant start and transient operation. Potential ammonia emissions due to SCR operation should be
Literature


Dear Ladies and Gentlemen,

Despite geopolitical and business challenges, it is with pleasure that we would like to cordially invite you to the “vgbe Congress 2022” in the beautiful port city of Antwerp.

The issues and challenges for the energy sector have not declined this year. Russia’s invasion into Ukraine has made it more than clear that a secure, affordable and sustainable energy supply is one of the core pillars of our society and of our economy. In recent years, the aspect of sustainability/climate protection had become the dominant factor in energy policy for good reasons, while economic affordability seemed within reach and security of supply was postulated as a given. In many countries natural gas was the fuel of choice to balance the fluctuating renewables and to pave the way to a green hydrogen economy. The increasing energy dependency on Russia for Europe was accepted because the availability of cheap natural gas from Russia and reliability of its supply was not challenged. Latest in March of this year we had all to learn the hard way that we made some wrong assumptions.

On the opening day, we want to discuss with high-ranking guests whether European policy has set the right framework conditions to enable the necessary investments in the energy system of the future. The challenges for this are enormous. What is needed is an increased expansion of renewables in power generation, whereby existing barriers in the area of approval procedures should be reduced and the market design optimized. Furthermore, an expansion of the necessary additional infrastructure in the area of energy storage and grids for gas, hydrogen and electricity is required.

Until this energy system of the future is in place and can provide a secure and independent supply of electricity and heat, we need to discuss again, how we want to provide dispatchable capacity and balance the renewables. We still have several options for this, but we need to choose one, or a mix of some of the options. What we cannot do, is pretending that we are already in the future and have already available green gases and other dispatchable renewable technologies. In this context, complex issues have to be clarified in terms of technology, affordability, climate protection and licensing law. It is up to policy makers to decide on the necessary measures. And we as an operators’ association are called upon to evaluate the technical options we have and support our member companies in implementing them.

In the technical part of the congress, we want to concentrate on the issues surrounding the topics of market and regulation, decarbonization, renewables and energy storage and repurposing of conventional generation sites with actual contributions and discussions in four sessions.

Networking, which we all missed so painfully during the recent Corona years, will also not be neglected between the sections and on the two evening events.

We would be delighted to welcome you as our guests in the appealing city of Antwerp.

be energised, be inspired, be connected, be informed

With energetic greetings

Dr Georg Stamatelopoulos
Dr Oliver Then

Online Registration
https://register.vgbe.energy/90122/

Contacts
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Ms Angela Langen | t +49 201 8128-310
e vgbe-congress@vgbe.energy
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With energetic greetings

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Ms Angela Langen | t +49 201 8128-310

Contacts

E vgbe-congress@vgbe.energy

Opening of the Congress

10:00 Opening speech
   Dr Georgios Stamatelopoulos, Chairman of the Board of Directors, vgbe energy e.V.

10:25 Welcome address
   Jacques Vandermeiren, CEO Port of Antwerp (tbc)

10:45 Honours
   • Innovation Award 2022
   • Health & Safety Award 2022

11:00 Report vgbe activities (vgbe 2025 & vgbe 100)
   Dr Oliver Then

11:30 Key Note Speech – Energy transition and security of supply in Europe
   Gerrit Jan Schaeffer, General Manager EnergyVille

12:30 Lunch Break

WEDNESDAY, 14 SEPTEMBER 2022 (CONT.)

Plenary Session – “Can we achieve security of supply and decarbonization with the existing regulation?”
   Moderation: Sonja van Renssen

14:00 Andreas Ehrenmann, ENGIE
   P1

14:15 Didier Van Osseelaer, Port of Antwerp-Bruges
   P2

14:30 Kristian Ruby, eurelectric
   P3

14:45 Jjorgo Chatzimarkakis, Hydrogen Europe (tbc)
   P4

15:00 Panel discussion
   Speakers P1-P4, Dr Georgios Stamatelopoulos and Gerrit Jan Schaeffer

16:00 End

16:30 General Assembly vgbe energy e.V.

17:30 Guided tour Chocolate Nation Museum (duration approx. 60 min.)

19:00 Evening event in the Chocolate Nation Museum
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### THURSDAY, 15 SEPTEMBER 2022

**Moderation**
Sonja van Renssen

#### Session A | Market & Regulation

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
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<tr>
<td>09:00</td>
<td>Results of the vgbe study “Security of supply 2025”</td>
<td>N.N., Fraunhofer IEE / vgbe energy</td>
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<tr>
<td>09:30</td>
<td>What does H2-ready mean for power plant industry?</td>
<td>Dr Jens Reich, STEAG Energy Services GmbH, Germany</td>
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#### Break
10:30

#### Session B | Decarbonisation

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<th>Time</th>
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<th>Speaker</th>
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<tr>
<td>11:00</td>
<td>MHI’s HydaptiveTM Concept for decarbonised power generation and energy storage. The US example</td>
<td>Dr Michalis Agraniotis, Mitsubishi Power Europe, Germany</td>
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<td>11:10</td>
<td>Haru Oni efuels – from vision to reality</td>
<td>Rolf Schumacher, HIF (Highly Innovative Fuels), Chile, and Alexander Tremel, Siemens, Germany</td>
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<td>11:20</td>
<td>Challenge Energy Transition – How to meet your utility demand in a secure &amp; climate friendly way</td>
<td>Martin Damerius, Uniper, Germany</td>
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#### Discussion
11:30

#### Break
12:00

---

### THURSDAY, 15 SEPTEMBER 2022 (CONT.)

#### Session C | Renewables & Storage

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
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<tr>
<td>13:00</td>
<td>Hydropower and taxonomy – Level playing field for renewables or imbalance?</td>
<td>Martin Schönberg, VUM Verfahren Umwelt Management GmbH, Austria</td>
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<tr>
<td>13:10</td>
<td>Hybrid solutions in the field of hydropower</td>
<td>Serdar Kadam, Andritz Hydro, Austria</td>
</tr>
<tr>
<td>13:20</td>
<td>CEOG: 24/7 power supply with PV, hydrogen and fuel cell</td>
<td>Mario Hüffer, Siemens Energy Global GmbH &amp; Co. KG, Germany</td>
</tr>
</tbody>
</table>

#### Discussion
13:30

#### Break
14:00

#### Session D | Repurposing

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:30</td>
<td>Repurposing overview from RECPP to other projects</td>
<td>Dr Thomas Eck, vgbe energy e.V., Germany</td>
</tr>
<tr>
<td>14:50</td>
<td>Technical Program hydrogen: Together on the way to a safe qualification of materials for the hydrogen industry</td>
<td>Barbara Waldmann, RWE Power AG, Germany</td>
</tr>
</tbody>
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#### Discussion
15:00

#### Wrap-up and Fare well
15:40

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**Online Registration**

[https://register.vgbe.energy/90122/](https://register.vgbe.energy/90122/)

**Contacts**

Ms Ines Moors  | t +49 201 8128-222
Ms Angela Langen | t +49 201 8128-310
e vgbe-congress@vgbe.energy
GET-TOGETHER
TUESDAY, 13 SEPTEMBER 2022
On Tuesday 13 September 2022 all participants are invited to join the get-together in the Radisson Blu Astrid Hotel.
- 18:00 to 21:00 – Room Aurora & The Diamond

PRACTICAL INFORMATION
VENUE
Radisson Blu Astrid Hotel, Antwerp
Koningin Astridplein 7B
2018 Antwerpen, Belgium
- +32 3 203 12 34
- https://t1p.de/g7r1x (shortlink)

REGISTRATION
Please register online at:
- https://register.vgbe.energy/90122/
Registration is possible until the day of the event. The list of participants will be made available online.

SIDE PROGRAMME
WEDNESDAY, 14 SEPTEMBER 2022
On Wednesday 14 September 2022 all participants have the opportunity to take part in a guided tour in the Chocolate Nation Museum in which later the evening event will also take place.
- Start 17:30 – Duration approx. one hour.

EVENING EVENT
WEDNESDAY, 14 SEPTEMBER 2022
On 14 September 2022 engie and vgbe invite all participants to an evening event in the Chocolate Nation right next to the Radisson Blu Astrid Hotel.
- Chocolate Nation – 19:00 to 23:00
Further information see

CONDITIONS OF PARTICIPATION
The participant fees for the vgbe Congress 2022 are as follows (incl. VAT, 21%):
- vgbe-Members 1,190.00 €
- Non-Members 1,690.00 €
- University, public authorities, retired 690.00 €
Students can obtain a free ticket for the entire lecture event upon presentation of a student ID (scientific staff excluded).

VGBE CONGRESS 2022 WEBSITE
- https://t1p.de/vgbe2022c

PRIVACY POLICY & GENERAL TERMS
More details are available on the vgbe* website at www.vgbe.energy/en/conditions-of-participation-privacy-policy

* vgbe energy has been the new brand identity of VGB PowerTech since September 2021 and the new name of the association since April 2022.