Simulation of the variable assembly of MGT-SOFC systems to optimize the mechanical efficiency

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Abstract
Simulations of various modifications and technical solutions to improve the energy yield when connecting micro gas turbines and SOFC high-temperature fuel cell systems are presented. Above all, heat integration measures enable an increase in system efficiency and a reduction in primary energy input. On the basis of analysis of efficiencies and the heat output it is shown, which high influence the modifications for the improvement of the hybrid process have on the energy yield. Finally, an optimal configuration is worked out, which enables primary energy to be used with the highest possible efficiency.

Particular emphasis is placed on the use of gaseous fuels from renewable energy sources. Preparation mechanisms, e.g., the reforming of used methane, and the improvement of the heat insulation materials was also taken into account. All in all, electrical total efficiencies for the optimized hybrid system of more than 65 % could be proven and additional thermal energy for heating purposes was extracted. Overall efficiency for the utilization of the energy content of the primary energy of up to 95 % was then achieved.

Entire systems with a maximum system output of around 270kW were examined. In the near future, these plants can replace existing fossil-fuel power plants. Due to the achievable flexibility, the previous security of supply and load fluctuation compensation can also be performed.

Keywords: MGT-SOFC, Hybrid System, Simulation, Fuel Cell, Micro gas turbine.

1. Introduction
One task to protect the climate is to reduce primary energy consumption. At the same time, the switch to renewable energy sources must be tackled [13]. The big problem here is the time difference between production and consumption. For example, the so-called dark lull is critical for the operation of a supply network. A method must be found to store energy generated from renewable sources safely and effectively for later conversion into electrical energy. For efficient storage, power-to-gas systems are
also an option if there is an efficient possibility of regenerating electricity. Efficiencies of more than 75% for the production of fuel gas (\(\text{CH}_4\)) and more than 80% for the production of pure hydrogen are already being achieved. There is no procedure for the efficient conversion of electricity back into electricity [1],[2],[4],[5].

In fuel cells, the direct conversion of chemical energy into electricity takes place through electrochemical processes. Direct conversion usually results in a higher system efficiency [7]. Among the highly efficient fuel cells are SOFCs (Solid Oxide Fuel Cells). These high-temperature fuel cells use membranes made of yttrium-stabilised zirconium oxide as solid electrolyte. This type of fuel cell can achieve an electrical efficiency of more than 50% at operating temperatures of more than 700°C under atmospheric conditions.

Simulations also show that an increase in the operating pressure of SOFC fuel cells can increase cell performance. It may therefore make sense to couple an energy converter that can convert energy under pressure and high operating temperatures with such cells. Efficient, recuperated micro gas turbines are a suitable solution for this purpose. They supply compressed combustion air which, after preheating, can be made available as cathode air for fuel cell conversion. The use of the components can be coupled in different ways to make better use of the primary energy input. With conversion of the residual fuel in an afterburner chamber, the electrical yield and the electrical efficiency of the entire system can be further increased with a turbine.

Various hybrid interconnection variants of micro gas turbines and SOFC stack clusters allow heat flows and energy conversions to be coupled in different ways. Selected arrangements are to be compared with each other using Ebsilon simulations [10] and heat analyses [8]. A circuit variant of the individual apparatuses will be worked out, which promises a maximum electrical efficiency for an entire machine. The simulation results will be presented and compared with each other and the influence of the selected individual components on the overall system will be discussed.

2. Determination of performance and efficiency of hybrid coupling of Micro gas turbines and SOFC fuel cells

To investigate the performance of hybrid systems consisting of SOFC high-temperature fuel cells and micro gas turbines, the electrical efficiency in relation to the lower heating value (LHV) of individual circuit variants is compared with each other. The overall efficiency of the hybrid system in terms of heat output and electrical efficiency also plays a role. Hybrid supply systems MGT-SOFC can be used both for local heating and electrical supplies [1].

In an SOFC fuel cell, the chemical energy of the fuel is directly converted into electricity by electrochemical processes ("cold combustion"). For their electrochemical reactions, such fuel cells use hydrogen as fuel, which is supplied to them either directly or as a fossil precursor. Air is fed to the cell as an oxidizer, separated by a solid oxide membrane. The oxygen contained there can diffuse ionised as \(\text{O}_2^\ominus\) at high temperatures through the membrane. On the anode side, these ions then react with the hydrogen to form water, releasing electrons and heat. The electron migration can be used as electric current via the connected electrodes [7].

\[
\text{Anode:} \quad \begin{align*}
2 \text{H}_2 + 2 \text{O}^\ominus & \rightleftharpoons 2 \text{H}_2\text{O}(g) + 4 \text{e}^\ominus \\
\text{CO} + \text{O}^\ominus & \rightleftharpoons \text{CO}_2 + 2 \text{e}^\ominus
\end{align*} \quad E_0=0 \text{ V} \quad (1)
\]

\[
\text{Cathode:} \quad \begin{align*}
\text{O}_2 + 4 \text{e}^\ominus & \rightleftharpoons 2 \text{O}^\ominus \\
2 \text{H}_2 + \text{O}_2 & \rightleftharpoons 2 \text{H}_2\text{O}
\end{align*} \quad E_0=1,23 \text{ V} \quad (2)
\]

Since a free enthalpy of the reaction of \(\Delta G_0 = 237.13 \text{ kJ/mol}\) and an enthalpy under standard conditions of \(\Delta H = 285.83 \text{ kJ/mol}\) can be determined, regarding the theoretical efficiency follows:

\[
\eta_{\text{rev, SOFC}} = \frac{\Delta G_0}{\Delta H} = \frac{237.13 \text{ kJ/mol}}{285.83 \text{ kJ/mol}} = 82.96% \quad (3)
\]
These 82.96% represent the theoretical maximum which can be achieved with the reacting substances H₂ and O₂. The efficiency of the fuel cell ($\eta_{FC}$) shows the ratio of supplied chemical energy and generated electrical energy, which summarizes the losses inside the fuel cell.

$$\eta_{FC} = \frac{\text{electrical power}}{\text{chemical performance in used hydrogen}}$$

This can be represented in an efficiency chain, so that the internal losses can be more specifically attributed to their origins and the Fuel Utilization of Hydrogen in the FuelCell Fu:

$$\eta_{FC} = \eta_{rev}^{SOFC} \cdot \eta_{U} \cdot \eta_{I} \cdot \eta_{H} \cdot F_{U}$$

In the system under investigation, the energy expenditure of the transformation from CH₄ to H₂ in the reformer reaction is taken into account for evaluation. In the turbo system, efficiency can be assessed on the basis of the individual efficiencies of compressor, turbine and mechanical coupling. To determine the el. efficiency, the generator efficiency is also required. All in all, this results in an electrical efficiency for the turbo machinery part [8],[11]:

$$\eta_{el,MGT} = \eta_{Comp} \cdot \eta_{m} \cdot \eta_{Tur} \cdot \eta_{Gen}$$

$$\eta_{el,Tur} = \frac{\text{electrical power}}{\text{chemical performance in used methane}}$$

### 2.1 Efficiencies for hybrid systems made of MGT and SOFC

In order to be able to compare different system circuits with each other, it is necessary to analyze the overall electrical efficiency with $\eta_{C}$ as the efficiency of the fuel conversion:

$$\eta_{SOFC-MGT}^{real} = \left( \eta_{MGT}^{real} + \eta_{SOFC}^{rev} \cdot \eta_{U} \cdot \eta_{I} \cdot \eta_{C} \cdot (1 - \eta_{MGT}^{real}) \right) \cdot \eta_{System}$$

For comparison, the power output of the fuel cell was kept constant. Therefore, the total mass flow of combustion air approximately was taken to be constant. These fixed points were used to compare electrical efficiency, overall efficiency and power output. This was used to determine which subsystem configuration has a positive influence on the performance of the overall system.

![Figure 1: MGT-SOFC-Hybrid Energy Converter](image)
3. Researched systems

First, a reference simulation for a MGT SOFC system with single-stage compression and turbine is presented. This system operates at 4.8bar abs. operating pressure and can convert a high degree of primary energy into electrical energy. SOFC stacks are used, which show their optimum operating point at 750°C. These are the operating conditions of an MGT SOFC of the TurboFuelCell 1.0 type, which is currently under development in the authors’ working group [1],[2],[5],[6],[14].

For comparison purposes, the number of stacks was kept constant and the power output of the entire system was kept similar. Care was taken to ensure that all the load cases examined had approximately the same primary energy input. Furthermore, both full load and partial load cases with a machine load of 50% were compared with each other.

![Standard simulation diagram full load](image)

**Figure 2:** Standard simulation diagram full load

3.1 Two-stage turbo system

In particular, if the compressor system is two-stage, impellers with a higher efficiency can be used. Above all, the gap losses can be reduced by lower pressure stages in the respective impellers. It will be investigated whether a uniform pressure staging of two impellers can be improved compared to compression with only one compressor impeller, but a larger pressure staging. A turbine wheel is to be used as the drive in the evaluation. A distinction is made between compression with intercooling and without such an extension. The influence of the heat deficit due to the changed compression stage on the overall process is also evaluated. The heat exchange for the intercooling process is done by a heat exchanger. An investigation of the injection of water for direct cooling can be found in [3].

3.2 Electrical separation of turbine and compressor

Especially for an optimization of the partial load behavior it is necessary to operate the turbine wheel and compressor wheel in a hybrid system at the optimum operating point. It may be necessary to operate both wheels in different load configurations and at different speeds. One possibility is to drive both systems with electric motors. For this purpose, it is being investigated whether the advantage of decoupled operation allows an increase in efficiency for the overall system. The efficiency of the electrical operation and the evaluation of an independent control system are of particular importance.
3.3 Optimization of heat management

Various circuits for optimizing the heat flow are being investigated for their influence on the overall system of an MGT-SOFC. The aim is to show that highly integrative circuitry improves the utilisation of the primary energy input. Furthermore, it will be shown under which conditions low-temperature energy can be made available.

3.4 Use of a turbine system with VTG guide vanes

By using a VTG (variable turbine geometry) guide grid in the turbine section, the efficiency and response of a radial turbine furthermore can be further increased. Thus, at the design point under full load, an optimum flow to the turbine wheel is set. By adjusting the inflow conditions in the partial load range, the response behaviour and efficiency of the turbine system is improved. This allows the compressor to operate in a significantly improved working range [12]. Thus, the gas flow can be optimally introduced into the machine for the required load range with the highest possible efficiency.

3.5 Optimization of the flow of the supply gases

Heat exchange, pipe losses and insulation expenditure for the entire machine can be optimized with suitable flow control. In particular, MLC airflow (MLC Multi-layer Containment for system isolation and media packaging) and pressure loss optimization can have a significant influence on the performance of the entire system. Variable guide grids are also used to optimize the load, especially in the partial load range. Overall, the electrical efficiency can be significantly improved by optimizing the pipe systems.

3.6 Influence of the stack load

It is shown to what extent the stack load can lead to degeneration and a change in the service life of the cell systems used. In particular, it is shown that an increase in the number of stacks certainly leads to an improvement in the stability and performance yield of the overall system.

4. Results

For comparison, a circuit corresponding to the structure of a TurboFuelCell 1.0 was simulated as a reference circuit. For this purpose, various adaptations of the plant schematic were examined in the 1D simulation program Ebsilon from Steag GmbH. For the standard model, the calculation data as shown in Table 1 were determined for an optimum efficiency and a system output of about 270kW.

| TurboFuelCell 1.0-Standard |  |
|---------------------------|--|
| Electrical Power delivered to grid | 278.21kW |
| Thermal Power | 124.50kW |
| Electrical Efficiency | 69.12% |
| Overall Efficiency | 99.82% |
| Electrical Power Fuel Cell/Turbine | 246.47kW/37.537kW |
| Fuel utilization/Efficiency Fuel Cell | 75%/54.58% |
| Reformer Steam/Carbon | 2.0 |
| Air in | 0.376kg/s |
| Fuel in | 8.066g/s CH₄ |
| Pressure ratio π | 4.65 |

Table 1: Performance data of the TurboFuelCell 1.0 Standard simulation

Due to the high electrical efficiency a very good utilization of the primary energy carrier methane is achieved. Heat recovery measures also help to achieve a high overall degree of utilization, whereby the thermal output can be used for heating purposes and low-temperature heat.
Table 2: Performance data Standard configuration

| Description                        | El. Efficiency | El. Power (kW) | Air Flow (g/s) | Fuel Flow (g/s) | Thermal Power (kW) | Overall Efficiency % |
|------------------------------------|----------------|----------------|----------------|-----------------|-------------------|----------------------|
| Standard simulation full load      | 69.12          | 278.21         | 376            | 8.066           | 124.5             | 99.82                |
| Standard simulation partial load   | 71.05          | 163.08         | 188            | 4.599           | 68.62             | 100.73               |
| Standard simulation partial load, VTG | 72.14          | 169.62         | 188            | 4.710           | 68.17             | 100.93               |

4.1 Study of the two-stage turbo system

The use of a two-stage compressor system reduces the required pressure step per impeller to the baseline having one pressure step [12]. This reduces the pressure ratio to 2.16 per stage while maintaining the same gap loss. Thus, the isentropic efficiency of each individual stage can be slightly increased. For the simulation, an increase in the isentropic efficiency per stage of 4% was assumed.

A two-stage compressor system results in a noticeable increase in the output of the entire machine. This shows that such a system can certainly provide advantages in terms of primary energy consumption, irrespective of more complicated flow control.

Table 3: Performance data of two stage compressor system, one shaft

| Description                        | El. Efficiency | El. Power (kW) | Air Flow (g/s) | Fuel Flow (g/s) | Thermal Power (kW) | Overall Efficiency % |
|------------------------------------|----------------|----------------|----------------|-----------------|-------------------|----------------------|
| Two stage compressor, full load    | 69.64          | 280.26         | 375            | 8.064           | 123.05            | 99.99                |
| Two stage compressor, partial load | 71.45          | 164.32         | 188            | 4.608           | 68.19             | 100.88               |
| Two stage compressor, full load, intercooler | 71.28          | 286.96         | 356            | 8.066           | 93.71             | 101.2                |
| Two stage compressor, partial load, intercooler | 73.2           | 169.52         | 177            | 4.639           | 52.41             | 102.05               |

A further improvement can be achieved by the use of intercooling (Table 3, line 3+4). This reduces the energy required for compression and increases the electrical efficiency. However, the dissipatable thermal power is also significantly reduced. The heat dissipated by the intercooling is missing in the heat balance to reach the stack operating temperature and has to be removed elsewhere. This means that part of the low-temperature heat is no longer available for heating purposes.

Figure 3: Simulation diagram two-stage system with VTG turbine system and intercooling
4.2 Investigation of the electrical separation of turbine and compressor

For better utilization of the impeller performance, especially in the partial load range, systems were investigated which allow the speeds of turbine and compressor to be varied differently. In particular, there is the possibility to strengthen the electrical generator of the turbine section and to drive the compressor wheel with the additionally gained energy. Thus, both systems can be operated in better efficiency ranges. The standard configuration and a two-stage compression were investigated, as well as the use of adjustable turbine geometries to improve the partial load behavior.

4.2.1 Standard Configuration with electrical separation

| description                                      | el. Efficiency % | el. Power kW | air flow g/s | fuel flow g/s | thermal power KW | overall efficiency % |
|--------------------------------------------------|------------------|--------------|--------------|---------------|------------------|----------------------|
| Standard simulation full load, electrically isolated | 67.54            | 271.79       | 376          | 8.066         | 124.5            | 98.24                |
| standard simulation partial load, el. isolated    | 69.57            | 159.64       | 188          | 4.599         | 68.62            | 99.24                |
| standard simulation partial load, VTG, el. isolated | 70.73            | 166.28       | 188          | 4.710         | 68.17            | 99.52                |

*Table 4: Performance data of standard turbo system, compressor/turbine on two shafts, electrical isolated*

If the compressor and turbine are separated in the standard configuration, the additional loss of efficiency due to the electrical conversion will come more in focus. Table 4 shows the calculation regarding this configuration. In spite of high efficiencies in high frequency electric motors and generators, the electrical efficiency in particular will decrease due to the additional double energy conversion under full load conditions. It is also to be expected that the electrical output of the overall system will be reduced, since the additional conversion loss requires more drive energy. Furthermore, a higher degree of efficiency can be expected under partial load than under full load, since the fuel cells achieve higher efficiency under lower load. However, the losses due to electrical separation cannot be compensated for by this increase.

By using a VTG system, an increase in turbine efficiency can be achieved, especially in the partial load range, through improved compressor delivery. Thus, the electrical output can be improved at the expense of the thermal power output.

4.2.2 Two-stage turbo system with electrical separation

Electrically separated systems, as listed in Table 5, do not provide any improvement in maximum efficiencies even in the two-stage variant. In all cases, the electrical results of the overall machine are below the respective mechanically coupled systems (impellers on one shaft). The decrease in efficiency due to the electrical separation is clearly visible in the electrical yield as well as in the additional thermal power available at full and partial load. A further problem for a timely realisation is the additional development effort required for the air bearing system required for a two-part system. This would then have to allow for a significantly improved controllability for different speed ranges.

| description                                      | el. Efficiency % | el. Power kW | air flow g/s | fuel flow g/s | thermal power KW | overall efficiency % |
|--------------------------------------------------|------------------|--------------|--------------|---------------|------------------|----------------------|
| two stage compressor, full load, el. Isolated    | 67.96            | 274.85       | 377          | 8.106         | 123.72           | 98.32                |
| two stage compressor, partial load, el. Isolated | 69.85            | 161.46       | 189          | 4.632         | 68.56            | 99.29                |
| two stage compressor, partial load, VTG, el. Isolated | 71.05            | 168.26       | 189          | 4.745         | 68.06            | 99.57                |
| two stage compressor, full load, intercooler, el. Isol. | 69.87            | 282.33       | 356          | 8.098         | 122.22           | 99.89                |
| two stage compressor, partial load, intercooler, el. Isol. | 71.89            | 167.21       | 177          | 4.660         | 67.78            | 100.83               |
| two stage compressor, partial load, intercooler, VTG, el. Isol. | 72.85            | 173.08       | 177          | 4.759         | 67.37            | 101.01               |

*Table 5: Two stage compressors, compressor/turbine on two shafts, electrical isolated*

4.3 Results from the optimization of heat management

Heat losses can be reduced by insulation measures. For this purpose, improved heat transfer can be realized by integrative measures and nesting of the apparatus parts. Heat transfer and pressure losses in pipe systems can also be improved by equalization of the flow and lowering the flowspeed. A decoupling of low-temperature heat for local heating concepts can cause an increase in the recoverable thermal
output at a flow temperature of 40°C compared to 80°C. Such a system can be used directly for feeding into underfloor heating systems and provides an additional heat quantity of 63.5 kW at full load. Modern low temperature heating systems operate with a 60°C/30°C flow/return interval. Even for such systems an additional heating cable of approx. 31.5 kW can be taken from the system. However, the utilization of the condensation of water, which is relevant to the calorific value, plays a considerably greater role in the gain in thermal output. The condensation water obtained in this way can also be used for the extraction of low-temperature heat.

4.4 Use of a turbine system with VTG guide grid (variable turbine geometry)

| Description                                      | El. Efficiency % | El. Power kW | Air Flow g/s | Fuel Flow g/s | Thermal Power kW | Overall Efficiency % |
|--------------------------------------------------|------------------|--------------|--------------|---------------|------------------|----------------------|
| Two stage compressor, partial load, VTG          | 72.55            | 170.97       | 188          | 4.721         | 67.69            | 101.07               |
| Two stage compressor, partial load, VTG, intercooler | 74.10           | 175.32       | 177          | 4.739         | 52.46            | 102.17               |
| Standard simulation partial load, VTG, isolated   | 70.73            | 166.28       | 188          | 4.710         | 68.17            | 99.52                |
| Two stage compressor, partial load, VTG, isolated  | 73.05            | 168.26       | 189          | 4.745         | 68.06            | 98.57                |
| Two stage compressor, partial load, intercooler, VTG, isolated | 72.85           | 173.08       | 177          | 4.759         | 67.37            | 101.01               |
| Standard simulation partial load, VTG             | 72.14            | 169.62       | 188          | 4.710         | 68.17            | 100.93               |

Table 6: turbine system with VTG (variable turbine inlet geometry)

By using adjustable turbine geometry, an additional increase in performance can be determined for both single-stage and two-stage systems, especially under partial load. Assuming that the maximum output can be achieved at full load with a suitable setting, the electrical efficiency of two-stage compressor systems increases to up to 74.1 % in the investigated partial load range of 50 % mass flow (see table 6). At the same time, however, the usable thermal output decreases for reasons already described above. This can be an advantage especially in the case of load requirements of low thermal power.

4.5 Optimization of the flow of the supply gases

The effort required to reach the cathode air temperature can be reduced by an additional heat input in the fuel gas flow and water heating already with the exhaust air flow. This results in a slight increase in the electrical efficiency. By converting the heating of the cathode exhaust air in counterflow compared to co-current flow, an improved heat exchange between cathode exhaust gas and cathode supply air can be achieved. If the preheating of the cathode supply air is forced by increasing the recuperator surface area, an improvement in heat coupling can be achieved and the surface area of the high-temperature heat exchanger can be reduced.

4.6 Influence of the stack load

By reducing the stack load, the fuel cells can be operated in a higher electrical efficiency range. This also results in longer service lives of the systems, as the degradation mechanisms are slowed down. However, this requires a higher number of fuel cell stacks to raise the power output to the standard value. The necessary, more complex distribution of the combustion air means that the distribution system must be further adapted. A marginal loss can be expected due to higher pipe resistances, but this will be compensated by the improved efficiency of the fuel cells.

5. Analysis

Various thermodynamic and technical measures are available to increase the efficiency of thermal turbo machines. These include above all cooling mechanisms and the increase in the number of stages of a turbo-compression. Here, a standard simulation was first carried out with a single-stage compressor and turbine and generator on the same shaft. Performance data were determined and for a standard system of a MGT SOFC (TurboFuelCell 1.0) having a maximum Power at start of operation of 278 kW an electrical efficiency of 69.12 % was determined. Derived from this, simulations were performed to estimate the influence of a two-stage compressor system, with and without intercooling, the efficiency improvement by a VTG system, and an electrical separation of the compressor and turbine systems.
Electrical and overall efficiency were then compared, as well as the additional thermal energy extraction for heating purposes and low-temperature heat.

A two-stage compressor system with intercooling can significantly increase system efficiency. When using a VTG system, higher efficiency can be achieved in some cases, especially in the partial load range, than under full load. This is due to improved compressor operation as well as improved efficiency of the fuel cell systems under lower load. The further improved stack efficiency through load reduction has a clear effect on system efficiency, but leads to more complex and larger systems, as more stacks are required for the same output. If intercooling is used, however, more exhaust gas energy must be used to reach the stack working temperature. This reduces the usable thermal output and the overall efficiency.

Electrical separation of turbine and compressor does not lead to any increase in efficiency in the systems investigated. An additional reduction in efficiency due to losses in the electrical drive technology cannot be compensated for by the efficiency increases of the overall system achieved as a result. This applies to both single-stage and two-stage systems and also systems with variable turbine geometry lead to a decrease in efficiency due to runner separation.

The most effective increase in overall efficiency was achieved by the VTG system. This enabled performance increases of up to 2% to be achieved, particularly in the partial load range. A coupled, two-stage system with VTG delivered the best performance in the partial load range. The compressor efficiency is stabilized in part load and less energy is required for compression, which can be taken from the turbine system as additional electrical energy. Based on the knowledge of the advantages of the VTG system, this system will also provide further advantages in turbine response and possibly enable an even more flexible system.

By reducing the working temperature of the exhaust gas heat exchanger, heat can also be extracted at the level of a 60°C/30°C low temperature heating system. There the overall efficiency will increase. A further use of waste heat for local heating concepts means an increased expenditure on equipment, but it can meet additional requirements if a corresponding reduction of the offered performance form is possible. Further concepts for cooling systems and direct heating systems with condensed exhaust air water are conceivable and will be dealt with in further work.

![Figure 4: Simulation of the variable assembly of MGT-SOFC-Systems to optimize the mechanical efficiency.](image-url)
efficiency of the Fuel Cell Stacks. For all the variants considered, this can be additionally increased by a further percentage point by the use of a VTG system. In contrast, decoupling the turbine and compressor sections with the help of electric drives and generator systems leads to a decrease in efficiency in all load cases considered.

6. Conclusion
Various simulations were carried out to investigate the influence of system additions to an MGT-SOFC (System TurboFuelCell 1.0). After comparing the variants, an increase in efficiency and performance could be achieved, starting from the standard system, mainly by VTG systems. However, two-stage compressor systems also achieved an improvement in electrical efficiency, especially when using intercooling. VTG systems can improve the response behavior and performance of the system, especially at partial load operating points.

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