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ENHANCING VVER1000 EFFICIENCY THROUGH GAS TURBINE INTEGRATION

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ABSTRACT

The development of sophisticated, effective, and sustainable power generation technologies is required to meet the expanding energy demands of modern society. Despite their benefits in generating electricity without direct greenhouse gas emissions, conventional nuclear power plants (NPPs) have relatively poor efficiency. This study investigates a new setup that combines a VVER1000 NPP with MGT-80 Gas Turbine Units (GTUs): a Combined Cycle Power Plant (CCPP). The third energy recovery loop in the integration uses the Supercritical Carbon Dioxide (sCO_2) Brayton Cycle or the Organic Rankine Cycle (ORC). The goal is to improve the NPP's steam cycle by utilizing the thermal potential of GTU exhaust gases, which will raise system efficiency overall. The Engineering Equation Solver (EES) program was used to create thermodynamic models, which were verified against operational data. Compared to standalone plant operations, the research shows that the suggested system structure offers greater efficiency and economic viability.

Introduction

Although humanity hasn't reached Type 1 civilization status, our position on the Kardashev scale is rapidly advancing. Scientific and industrial revolutions have speeded up the development of our technology. Recent breakthroughs in artificial intelligence have further increased this demand. For example, a single ChatGPT query consumes about 0.0029 kWh—nearly ten times that of a Google search—collectively, ChatGPT uses roughly 2.9 million kWh daily. This is equivalent to the daily energy use of 100,000 average U.S. households. Therefore, our energy consumption has increased not only linearly but also exponentially from the early 1800s, as we can see in Figure 1 [1]. In addition to this exponential increase in energy demand, limited fossil fuel supplies, and climate change push the global energy industry to adopt more efficient and sustainable technology. To achieve that we need to build new eco-friendly power plants or increase the power and efficiency of the current ones. Building new facilities is expensive and takes much more time than increasing the current ones` capacity and efficiency. Previous studies [2, 3] showed that the efficiency of the VVER1000 of the Bushehr nuclear power plant can be increased. In this study, we aim to increase the efficiency of Bushehr NPP, as well as the capacity, by adding Gas Turbines.

Due in large part to lower operating pressures and temperatures than fossil-fueled systems, nuclear power's moderate thermal efficiency of about 33% limits its potential as a substantial part of the low-carbon energy mix.

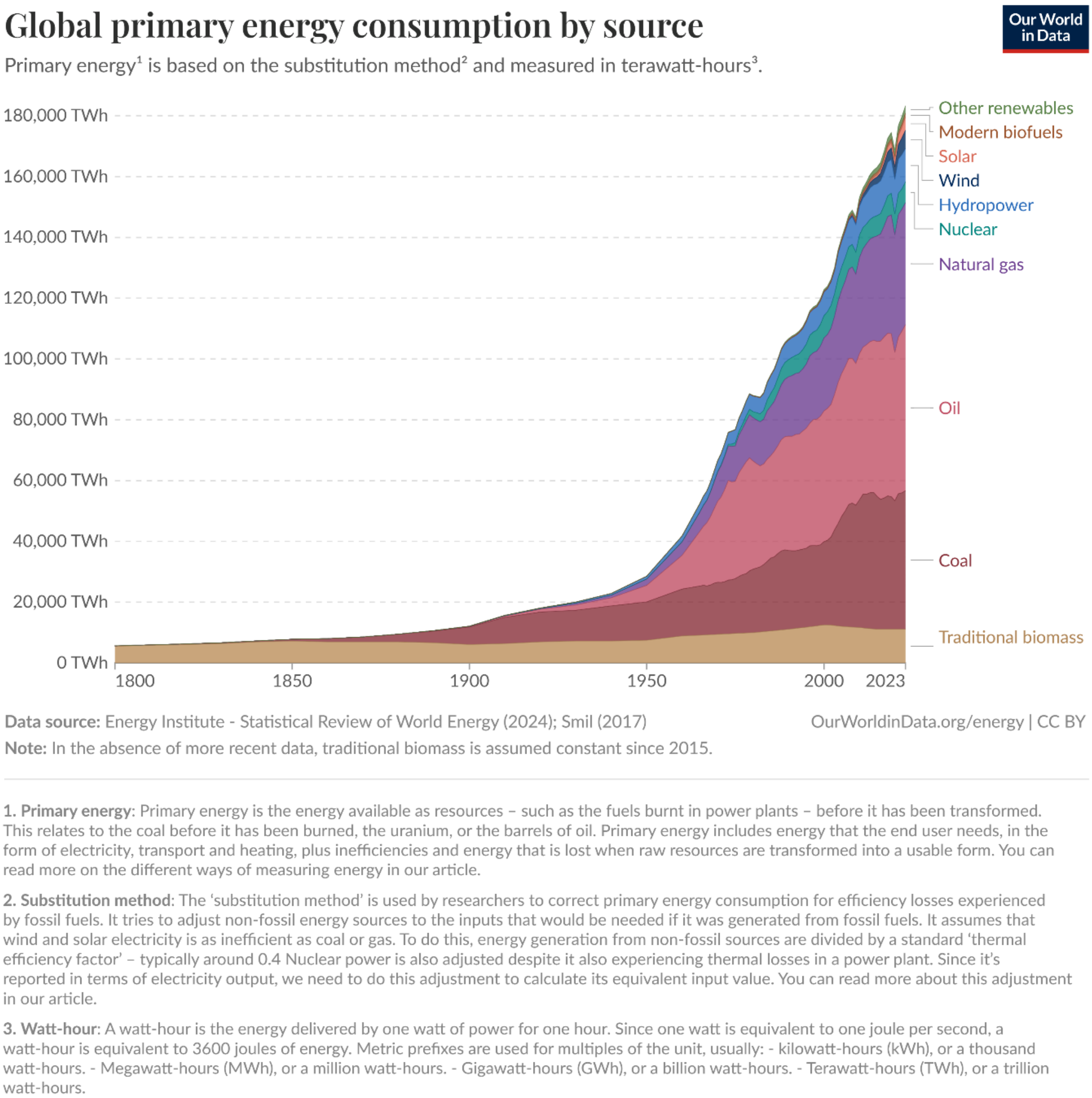

Figure 1. Global primary energy consumption. [1]

In the meantime, NPPs and Gas Turbine Units (GTUs), renowned for their quick deployment and adaptability, can be strategically combined. When coupled with heat exchangers, their high-temperature exhaust gases offer a chance for enhanced heat recovery and steam production. The possibilities of merging several MGT-80 GTUs with a VVER1000 NPP. Using sophisticated simulation in EES software, the integration seeks to maximize operational performance and thermal efficiency. The study evaluates the technical and thermodynamic viability of each component cycle by modelling it separately and then in combination.

The characteristics of the NPP

The commercially available NPPs are PWR, BWR, and PHWR known as CANDU. The steam generated to drive the steam turbines in these NPPs is almost saturated steam of relatively low pressure, compared to that in fossil power plants. With technological advancements, fourth-generation nuclear reactors can achieve efficiency levels of approximately 45%. However, commercially operated reactors typically exhibit efficiency levels ranging from 33% to 37%. In the previous studies, the NPP of the Bushehr nuclear power plant using PWR, known as VVER1000 was discussed and a detailed exergy analysis has been made.

Table 1. Principal features of the VVER1000 NPP. [3]

Reactor core thermal power output (MW_{th})	3000
Coolant flowrate (kg/s)	16800
Net thermal efficiency (%)	33.33
The pressure of the coolant at the core outlet (MPa)	15.7
The temperature of the coolant at the reactor outlet (°C)	321
Coolant heating in the reactor (°C)	30
The difference in the pressure in the reactor (MPa)	0.381
Number of loops (pcs)	4
Feedwater temperature at steam generator inlet (°C)	224
Steam temperature after steam generator (°C)	280
Steam pressure (MPa)	5.88
Steam flow rate (kg/s)	1661.11
Enrichment of the fuel - UO_2 (%)	3.6-4.95

To meet the Soviet Union's increasing demand for reliable and effective electricity sources in the 1970s, the VVER1000 nuclear power station was built. It is an improved version of the VVER440 NPP, which was created in the 1960s. The VVER1000 transfers heat from the core to the steam generators, which create the steam that powers the turbines and generates electricity, using a pressurized water system. Compared to other NPP models, the VVER1000's architecture enables it to function at higher temperatures and pressures, which increases efficiency. [4] The main characteristics of the VVER1000 NPP steam cycle are given in Table 2. The VVER-type nuclear power plant has gained widespread adoption in various countries, including Belarus, China, the Czech Republic, Finland, Germany, Hungary, India, Iran, Russia, and Turkey. This widespread adoption is due to the plant's reputation for reliability, efficiency, and advanced safety features.

Several cutting-edge safety features are included with the VVER1000. These include an emergency core cooling system to prevent fuel rods from overheating and melting in the event of a coolant loss accident and a double containment system to prevent the escape of radioactive material in the event of an accident. The reactor also has a passive heat removal system that may release heat from the core in an emergency without the need for outside power or assistance.

To improve the efficiency of the NPP cycle, the hot gases released from these GTs can be used to superheat the steam produced in the NPP before it enters the steam turbines. Additionally, by preheating the feed water that returns from the condenser to the NPP's steam generators, these gases can boost the plant's power output. More power will be produced by utilizing the steam drawn from the NPP steam turbine for the feed heaters. To put it briefly, the efficiency and power production of both cycles may be greatly increased by combining the gas turbine GT cycle with the NPP.

The steam cycle of the suggested VVER1000 NPP

Figure 2 shows a schematic diagram of the VVER1000. The first loop of VVER1000 transfers heat from fission in the reactor to the steam generators. The steam produced is then sent to the steam turbine through a secondary loop. The steam cycle includes high-pressure turbines, low-pressure turbines, a moisture separator, a reheater, closed-feed water heaters, a deaerator, a condenser, and an electric generator. The produced steam has a mass flow rate of 1661.11kg/s and is nearly a saturated vapour at a pressure of 5.88MPa and a temperature of 274.3C. In the high-pressure turbine, the steam expands to a mid-pressure level (P10), aiming for a steam quality (x10) of more than 0.86. The extracted steam from the high-pressure turbine is directed to the high-pressure feed water heater 5 and the deaerator. The isentropic efficiency is 0.957 for the high-pressure turbine and 0.8637 for the low-pressure turbine. At the exit of the high-pressure turbine, the steam conditions are as follows: P10=770KPa, T10=168.8C, x10=0.861, and h10(enthalpy)=2482.4kJ/kg. Following its expansion in the high-pressure turbine, the steam proceeds through a reheater and a moisture separator. Moisture is extracted in the moisture separator and sent to a low-pressure feed water heater running at 741KPa. The reheater generally has a 33KPa pressure loss, resulting in a steam pressure of P14=708KPa. In order to raise the steam temperature, there is also a direct steam supply from the steam generator to the reheater, and the condensed steam is directed to the reheat cooler (RHC). Three steam extraction lines from the low-pressure turbine are directed to the low-pressure feed water heaters 3, 2, and 1, operating at pressures of 196, 86.2, and 35.3 KPa, respectively. After the low-pressure turbine, the steam goes to the condenser with a pressure of 7.5KPa, 40.3C, and 2328.7kJ/kg enthalpy. [4, 5]

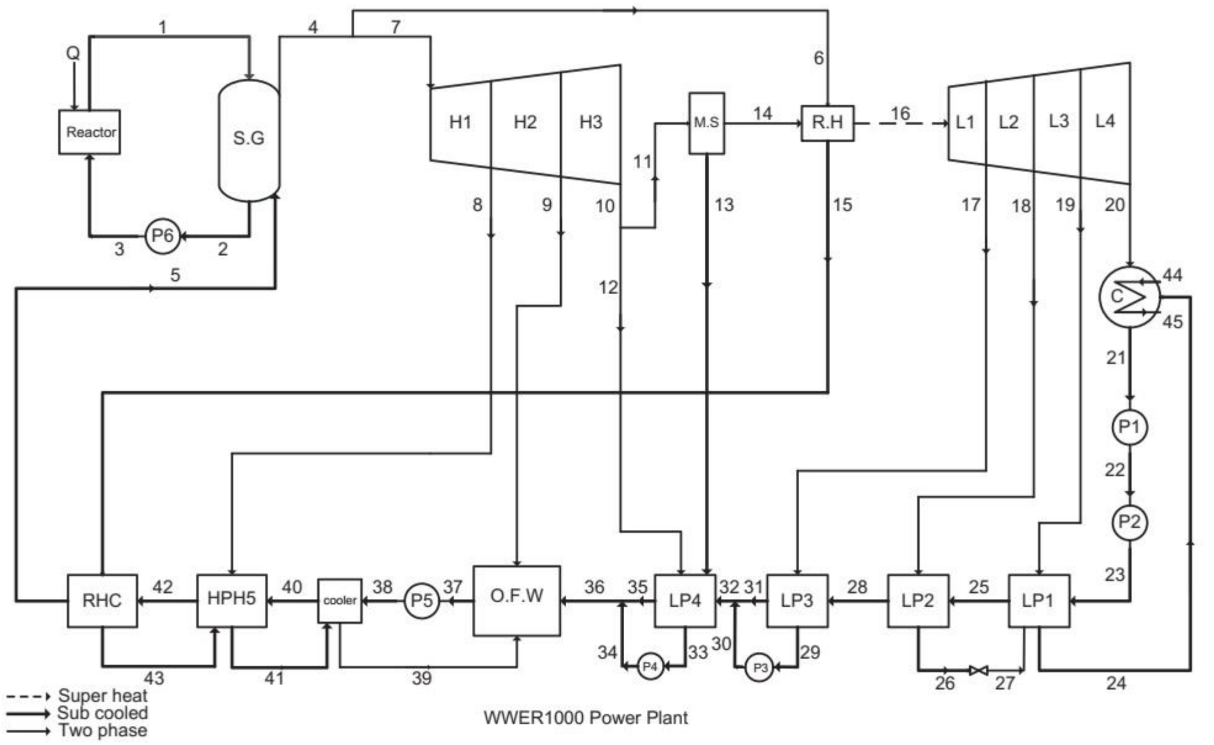

Figure 2. A schematic diagram of the VVER1000 steam cycle. [2]

Gas turbine unit

The gas turbine selected for this study, the MGT-80, is manufactured and developed by the Iranian technical company MAPNA Group. This heavy-duty gas turbine has a gross efficiency of up to 40% and a significant nominal power output of 308 MW. The MGT-80 has a 15-stage axial flow compressor, a dry low-emission combustor with 24 burners, a 4-stage axial power turbine, and a generator.

Atmospheric air enters the compressor with a particular mass flow rate ($\dot{m}_{air}$), temperature, and pressure. After passing through the compressor with a pressure ratio (PR) of 19, the air exits the compressor at a determined pressure. Fuel is injected, ignited, and burned in the combustor downstream of the compressor at a specific fuel flow rate ($\dot{m}_{fuel}$).

The turbine inlet temperature (TIT), which represents the highest temperature (T_2) in the cycle, is achieved when the combusted mixture of air and fuel, at a specific flow rate ($\dot{m}_{gas}$), exits the combustor and enters the turbine. The turbine transforms the energy of the expanding hot mixture into work. The expanded gases leave the gas turbine as exhaust at a particular temperature and pressure.

If the gas turbine is equipped with a heat recovery steam generator (HRSG), it can recover waste heat at this stage and produce steam. This steam can then be utilized for process heat, space heating, or to drive a steam turbine for additional power generation. The performance data of the gas turbine unit are outlined in Table 2.

Table 2. The performance data of MGT-80 gas turbine. [5]

Gross Power Output (MW)	308
Gross Efficiency (%)	40.1
Turbine Inlet Temperature (°C)	1265
Exhaust Gas Temperature (°C)	581
Exhaust Mass Flow Rate (kg/s)	724
No. of Compressor Stages (EA)	15
No. of Turbine Stages (EA)	4
Pressure Ratio	19
Type of Combustors	Annular, 24 Burners

Modified combined NPP-GT analysis

This chapter examines the technical feasibility and potential benefits of integrating gas turbine units into a nuclear power plant. The goal is to increase the nuclear facility's overall efficiency and power-producing capabilities. We used modern modelling techniques and thorough analysis based on relevant books and scientific journals.

Using the EES software package, we developed a trustworthy computational model to analyse and simulate the proposed integrated system. This model took into account several important factors, such as thermodynamics, heat transfer, fluid dynamics, and system dynamics. The simulation model was created to accurately replicate the behaviour of integrating gas turbine units with a nuclear power station in the actual world by utilizing empirical data and previous research findings.

We assessed several crucial performance metrics using the simulation, including the system's overall efficiency, power output, and long-term viability. To quantify these characteristics and determine the potential advantages and disadvantages of the integrated system, we carried out a comprehensive analysis. The technological feasibility, and operational characteristics of integrating gas turbine units with a nuclear power station are explained in this paper.

The study's findings contribute to the body of scientific knowledge already available on nuclear power generation and offer wise counsel to academics, decision-makers, and industry experts who wish to explore innovative strategies for enhancing the sustainability and effectiveness of nuclear energy systems.

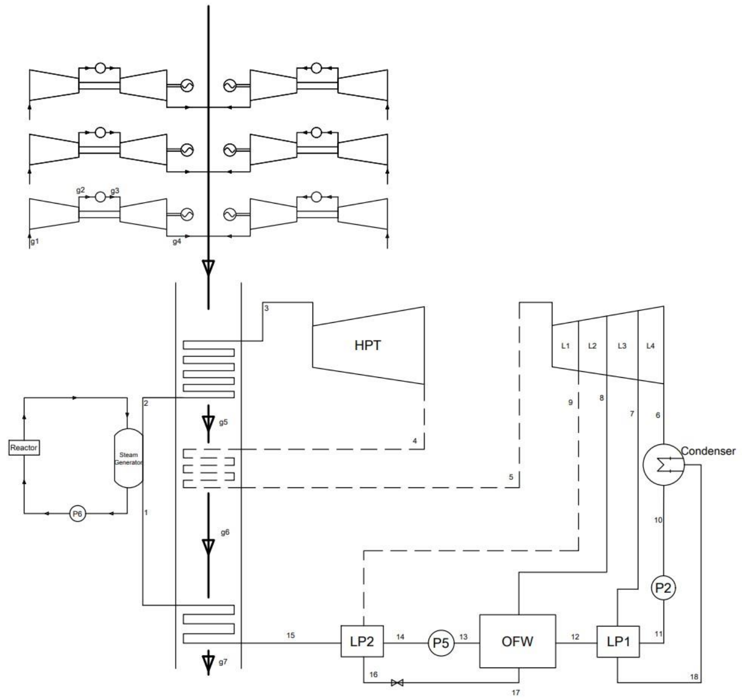

Figure 3. A simplified illustration of the GT-NPP combined cycle.

A possible strategy to increase power generation efficiency is the integration of gas turbine units into nuclear power plants, often known as a GT-NPP combined cycle. The gas turbine's exhaust waste gases raise the steam temperature after the nuclear power plant's steam generator in this combined cycle. This enables a more effective utilisation of the heat produced by the nuclear reactor, as the gas turbine's exhaust gas can complement the reactor's heat generation. Figure 3 presents a simplified illustration of the GT-NPP combined cycle.

The nuclear reactor and the gas turbine operate as independent systems in the GT-NPP combined cycle. Whereas the nuclear reactor creates heat by fissioning uranium or other nuclear fuels, the gas turbine uses natural gas or other fuels to produce electricity. A steam generator is used to boil feed water and create steam by transferring the heat from the nuclear reactor's core to a seperate circuit. This steam then drives multiple steam turbines that, in turn, generate electricity. The temperatures of the steam after the steam generator (around 250-300) and the exhaust gases (around 550-600) of the GTU differ significantly. So, in an additional stage of CCPP, the exhaust gas from the gas turbines passes through another section of the heat exchanger to increase the steam temperature further before expansion in the turbines, thereby optimising the use of the nuclear reactor's heat. [6]

When compared to traditional power plants, the VVER-1000's present thermal efficiency of about 33% is rather low. This is mainly because the steam does not enter the turbine in a superheated state. Furthermore, around 30% of steam extraction must come from the steam turbines to heat the feed water coming back from the condenser to the steam generator and to reheat the steam leaving the high-pressure turbine before it enters the low-pressure turbine. As a result, the main flow's mass flow rate is lowered, which lowers the overall work output. So, integrating gas turbine units (GTUs) and nuclear power plants (NPP) is an effective way to increase efficiency and power output significantly. This can enhance the availability of steam, thereby increasing the work output of the steam turbine, by elevating the steam temperature delivered to the high-pressure turbine of the NPP.

The waste heat from the GTUs' exhaust gas can be used to increase the steam's temperature by using a superheater, which is comparable to the heat recovery steam generator (HRSG) of combined cycle power plants (CCPPs). As exhaust gases maintain their relatively high temperatures after the superheater section (around 300°C), this waste heat can also be used as a reheater between high- and low-pressure turbines and as an economizer to heat the feed water delivered to the NPP's steam generator (SG) from the steam condenser. When feedwater heaters, a moisture separator, and a reheater are eliminated from the nuclear power plant's steam cycle, steam is not extracted from turbines. This allows more steam to expand in the turbine and produce more power.

The proposed GT-NPP combined cycle, illustrated in Figure IV.8, incorporates six MGT-80 gas turbine units and the VVER1000 with its stream cycle. This modified design utilised two low-pressure-closed feedwater heaters and a deaerator (open feed water heater). Unlike the original VVER1000 setup, we excluded the reheat cooler, a high-pressure-closed feedwater heater, a cooler, and two low-pressure-closed feedwater heaters. We used hot gases from the six MGT-80 gas turbines to superheat the steam before the high-pressure turbine, reheat it in between the turbine's two stages, and preheat the condenser's feed water to the steam generator. Only the installation of heat recovery steam generators (HRSG), which are a superheater, reheater, and economizer, was necessary to do this without changing the NPP steam-generating process.

Table 3. Given data from previous research papers. [3, 4, 6]

T_{g4}	Gas temperature at gas turbine outlet (°C)	581
P_1	Steam pressure at steam generator inlet (MPa)	5.88
T_1	Steam temperature at steam generator inlet (°C)	224
T_2	Steam temperature at steam generator outlet (°C)	280
P_6	Steam pressure at extraction 6 (MPa)	0.196
P_7	Steam pressure at extraction 7 (MPa)	0.0862
P_8	Steam pressure at extraction 8 (MPa)	0.0353
P_9	Steam pressure at extraction 9 (MPa)	0.0075
η_{HPT}	HP turbine	95.72
η_{LPT}	LP turbine	86.37
η_{p2}	Main condensate pump 2	92.08
η_{p5}	Main condensate pump 5	96.9

Data from previous sources was used to model this configuration, and some assumptions have been made, shown in Table 3 and Table 4, respectively. The turbine and pump efficiency, the steam generator's inlet and outlet temperatures (from the nuclear reactor's safety perspective), and the pressure readings are identical to those found in earlier studies [3, 4, 6]. At the same time, all heat exchangers are taken to be isolated devices (η=1) and small kinetic and potential energy differences are ignored. The temperature difference between the hot medium's inlet and the cold medium's outlet is mainly considered 10°C in closed feedwater heaters (LP1 and LP2), while in HRSG, this difference is 15°C. It is worth to note, T_{g7} is used when n={3,4,5} and T_3 is used when n={6,7}.

Table 4. Assumptions made to simulate.

T_{g4}	Gas temperature at gas turbine outlet (°C)	581
T_{g7}	Gas temperature at ecomoniser outlet (°C)	120
T_3	Steam temperature at superheater outlet (°C)	565
T_5	Steam temperature at reheater outlet (°C)	T_{g5}+15
T_{12}	Water temperature at outlet of LP1 (°C)	66
T_{17}	Steam temperature at outlet of LP2 (°C)	T_{14}+10
T_{19}	Steam temperature at outlet of LP1 (°C)	T_{11}+10

The superheater section's inlet temperatures of steam (280) and exhaust gases (581) and their mass flow rates are known. To maximize heat transfer while taking technological constraints into account, the ideal output temperatures for steam and exhaust gases are acknowledged to be 565°C and 300°C, respectively. Thus, we can find the minimum number of GTUs:

$$n * \dot{m}_{gas} * \left(h_{g4} - h_{g5}\right) = \dot{m}_{steam} * (h_3 - h_2)$$

where n is the number of GTUs, $\dot{m}_{gas}$ and $\dot{m}_{steam}$ are mass flow rates of a single gas turbine and NPP, h_{g4}, h_{g5}, h_3 *and* h_2 are enthalpy values of those points on the cycle. By solving this equation, we can found n as 5.327. This means we should have a minimum of 6 GTUs to achieve maximum heat transfer in the superheater section. Even though this configuration needs a minimum of 6 GTUs for the maximum heat transfer in the superheater section, to find the optimal number of GTUs for the cycle efficiency, we have simulated the same cycle with n={3,4,5,6,7}. Knowing the effectiveness of the reheater and LP2 at the same time is preferable. We should have enough heat supply to the system to add a reheater section. However, when n<6, we can neither reach the possible maximum temperature (565) for the steam entering the turbine (T3) nor decrease the exhaust gases` temperature after the superheater section until 300. The need for an economiser can explain the main reason for this issue. Due to the removal of several components from the cycle, which were heating steam entering the steam generator, an economiser needs more heat input. According to this information, we did not perform a simulation, where we have reheater, for the cases n<6. You can see the generated data in

Table 0.

Table 0. Results of the simulation.

n	RH	LP2	T_3 (°C)	T_{g5} (°C)	T_{g7}(°C)	W_{net} (MW)	⊚ (%)
7	+	-	565	317.9	162.6	4418	45.88
	+	+		317.9	193.2	4358	45.54
	-	-		367.2	211.9	4289	44.54
	-	+		367.2	240.8	4259	44.23
6	+	-		298.4	117.3	4040	46.54
	+	+		298.4	152.1	4009	46.18
	-	-		331.5	150.4	3970	45.72
	-	+		331.5	184.1	3940	45.38
5	-	+	529.5	314.2	120	3551	45.91
	-	-	504.5	337.3		3512	45.40
4	-	+	431.1	362.8		3014	44.41
	-	-	407.5	391.6		2981	43.91
3	-	+	341.7	443.7		2503	42.86
	-	-	322.1	482.2		2476	42.40

Analysis and Discussion

With a stunning 46.5% gain in thermal efficiency while using six GTUs, the integration of VVER1000 with MGT-80 gas turbine units has produced a much more efficient system. Comparing this to the respective efficiencies of MGT gas turbines (34%) and commercial nuclear power reactors (33%), there is a noticeable improvement. Several changes are responsible for the efficiency gain. A superheater has been installed in the GT-NPP combined power plant to raise the steam temperature from 280°C to 565°C, improving the steam availability. In addition to increasing the overall output work, reheating steam between high- and low-pressure turbines assisted in bringing the exhaust gas temperature down to about 120C. The HRSG's economizer now manages the process of heating the returning feed water from the condenser to the steam generator, doing away with the requirement to extract steam from the high-pressure turbine. Additionally, more steam expands in the turbines as a result of the removal of a reheater, a moisture separator, and feedwater heaters, producing greater power.

The power output of the improved VVER1000 has increased by an impressive 112.5% to 2125 MW. Consequently, the GT-NPP combined power plant's total power production is 4040 MW, which is 41.9% higher than the combined power output of the individual power plants, which comes to 2848 MW (1000 MW + 6 x 308 MW).

Better use of high-temperature exhaust, reduced thermal losses, and optimal load distribution among system components were credited with the efficiency increases. These findings were corroborated by energy analysis, which showed that the improved system has less irreversibility.

Conclusion

This study offers a solid framework for strategically integrating gas turbines and low-grade heat recovery cycles to increase the sustainability and efficiency of nuclear-based power generation. Significant gains in thermal efficiency and economic performance can be made by combining five MGT-80 GTUs with a VVER1000 NPP.

The suggested system layout provides a scalable answer to today's energy problems, especially in areas looking to increase nuclear capacity while reducing their environmental impact. The EES-based modelling and simulation demonstrated the approach's practical viability and offered precise thermodynamic insights.

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According to our baseline models, each MGT-80 GTU produces roughly 308 MWe at 34% efficiency, while a solo VVER-1000 generates about 1,050 MWe at about 33% thermal efficiency. The total net production increases to 4,040 MWe and the thermal efficiency rises to 46.5% when six GTUs are integrated with the NPP's steam cycle, rerouting their combined exhaust through economizers and superheaters to elevate steam conditions. Without using more fuel, this results in a power output increase of 41.9% and an efficiency gain of 13 percentage points compared to separate operation.

In terms of operation, the hybrid plant seamlessly responds to peak demand by combining the GTUs' quick start-up (±30 MW/min) and load-following capabilities with the NPP's steady base load. Environmental benefits include lower water use through closed-loop cooling in the tertiary cycles and the avoidance of almost 2.2 million tons of CO_2 annually when compared to simple-cycle GTUs.

The findings support the idea that combining various thermal cycles into a single power-generating platform can be crucial to the shift to more efficient and sustainable energy systems. Future studies should include dynamic load-cycle simulations, and real-world integration issues such waste-heat management, safety procedures, and regulatory compliance. To validate model predictions, pilot-scale demonstrations or experimental validation would be crucial.

In conclusion, the suggested GT-NPP combined cycle shows notable gains in output, economic performance, efficiency, and environmental effect. This arrangement presents a viable route toward more flexible, and sustainable power generation by efficiently recovering GTU waste heat to superheat nuclear steam.

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