A Literature Review of the Kalina Cycle and Trends

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Abstract. The demand for electricity and power has been increasing with the increase of the population of the world. The Covid-19 Pandemic has affected the way of life of human beings starting last year. The pandemic and economic downturn also affected the electricity demand of the world, but this is only short-term. Once the lockdowns around the world ease and back to normal situation begin, demand for power and electricity shall continue to grow. The century-old Rankine cycle has been the basis for power plants widely used today. However, a modified Rankine cycle known as the Kalina cycle has been proving more efficient than the standard Rankine cycle and might be able to provide the additional power needed in medium and low-temperature sources and waste heat recovery. This paper look into the development of the Kalina cycle and the trends that might be of use for the global electricity requirement.

1. Introduction
Electricity is a necessity in the daily lives of all human beings. The demand for it increases every year with the increase of the population of the world. An increase in the capacity and efficiency of the power plants is also needed for the generation of electricity. From Thermodynamics, the Carnot cycle is the most efficient, but it is the century-old steam cycle running on the Rankine Cycle that is widely used today. A modification of the Rankine cycle using ammonia-water mixture as the working fluid was developed by Alexander Kalina [1]. This paper will look into the cycle and the research showing the Kalina cycle's application to various energy systems, including internal combustion engines, gas turbines and renewable energy sources.

2. The Cycle
Alexander Kalina [2] invented a cycle that could rival the Rankine cycle in efficiency and effectiveness in waste energy recovery. Kalina’s Texergy cycle [3] was demonstrated using waste heat from a Diesel engine and was compared to a Rankine cycle. The results showed that the Texergy cycle has higher efficiency due to the flexibility of the boiling point temperature of the fluid used by Kalina proving the effectiveness of the cycle for cogeneration.

Another demonstration of the superior performance of the Kalina cycle to the Rankine cycle as a bottoming cycle in a combined-cycle system with a gas turbine was presented by Kalina in 1984 [4]. The cycle is said to be able to have 45% efficiency in heat conversion of a direct-fired system and 52% for a combined-cycle using the exhaust of the gas turbine [5]. Several gas turbines available in the market were analyzed to get the performance of the Kalina cycle for utility combined cycle. Improvement of 16-32% was recorded [6].

In 1988 an experimental project for a 3 MW kalina Cycle to be installed at the Canoga Park in California by US Department of Energy’s Energy Technology Engineering Center (ETEC) [7]. The working fluid for the plant is at 70% ammonia and 30% water mixture. This would be the first actual Kalina plant. It
was also at this time that the Kalina cycle was considered for the exploitation of geothermal resource at 360°F (moderate temperature) using ammonia/water, isobutene/heptane and refrigerants 22 and 114 and later propane and benzene were used as working fluids [8]. Results showed that the Kalina cycle is more effective using the ammonia/water as the working fluid.

Interest in the performance of the Kalina cycle providing higher efficiency and more power grew, and several studies were conducted to prove the concepts that Kalina set out. A simplified Kalina cycle (Figure 1) was considered for parametric analysis by Professor Marston from The department of ME at Villanova University [9]. Simulation of the cycle was based on the parameters used by Kalina, El-Sayed and Tribus and actual communication with them.

A Thermodynamic and exergy analysis of the Kalina cycle was conducted by Stecco and Desideri from The Italian Department of Energy Engineering [10]. The simulation showed that the exergetic efficiency of the Kalina cycle is maximized with optimized ammonia mass fraction and showed advantages over the Rankine cycle without changing the configuration of the cycle.

Wall, Chuang and Ishida [11] presented the exergy analysis of the Kalina cycle using the Energy-Utilization Diagrams (EUD). The diagram in Figure 2 showed that the highest loss of exergy from the components can be found at the boiler. This was compared with the initial analysis of the Kalina cycle and provided evidence of the severe pinch points of the original design [12]. Similarly, EUD of the Rankine and Kalina cycles using the ASPEN plus simulator and Fortran was conducted [13].

Analysis using the first law and second law of thermodynamics at the same thermal boundaries was used to compare the Kalina and the Rankine cycles [14]. The results showed that the Kalina cycle is superior by 5% for the first law efficiency and 15% in the second law efficiency.

Different configurations of the Kalina cycle were designed for study with increasing complexity to determine the potential efficiency gain from each system [15]. The simplest of these cycle is the KC0 with only one heat exchanger in the loop and was conceptualized due to an inquiry regarding a simple cycle with a two-component circulation. KC1 is suited for student projects and studied by Marston [9] is a simplified version of KC2 (Figure 3) that was studied and analyzed by El-Sayed and Tribus. KC1 can generate optimal efficiency at 55-60% Ammonia-water concentration. KC3 is the multi-stage configuration with the inlet pressure of the turbine is at 16,500 kPa (~2400psi) while KC0 to KC2 are designed for 10,000 kPa (~1450psi). KC1 and KC2 are comparable in efficiency while KC3 (Figure 4) is an improvement with a higher operating pressure.

**Figure 1**: Simplified Kalina Cycle [9]  
**Figure 2**: Energy-Utilization Diagram (EUD) of a Simplified Kalina cycle [11]
Kalina designed further developments of the system for gas turbine bottoming cycle and named it as KCS6 (Figure 5) or Kalina Cycle System 6 [16]. The system is composed of a heat recovery boiler, 3-stage turbine and regenerative heater. What separates this cycle to a traditional steam cycle is the Distillation Condensation Subsystem (DCSS). The KCS6 turbine provided 16.4% more output compared to a steam bottoming cycle.

KCS11 or Kalina Cycle System 11 was developed for the low temperature geothermal resource. KCS17 which is known as the hybrid Kalina cycle was designed as answer to the double flash geothermal system. The hybrid system power output was compared with the conventional and double flash geothermal system and yielded 86.7 MW as compared with the 55 MW of the conventional and 73.4 of the double flash system.

The cycle was evaluated together with the single and double flash systems and the closed Ranking cycles with regeneration using pure ammonia. KCS12 performed when in temperature at 210°C but was so restricted due to the complexity of the system. The regenerated Rankine cycle using closed heat exchanger was found to be promising in this study.

Another renewable energy system that considered the use of the Kalina cycle to improve its performance is the Ocean Thermal Energy Conversion (OTEC)[18]. OTEC uses temperature difference the ocean’s warm surface and the cold water from the sea depths. The study showed that the Kalina cycle has a 5% efficiency while the Rankine cycle was 3% efficiency when used in the OTEC system. Kalina also has 20% higher power output compared to the closed Rankine cycle.

More Kalina cycles were developed to address specific applications. The Kalina Cycle System 5 or KCS5 is used for direct fired plants and Kalina Cycle System 11 or KCS11 was developed for the low-temperature geothermal resource exploitation [19].
Exergy analysis of the Kalina cycle with the ammonia-water mixture properties modelled using the Peng-Robinson two-constant equation of state together with the Gibbs free energy equations of mixture [20]. The study determined that the turbine inlet condition and temperature of the separator are the key parameters for the cycle. The use of Peng-Robinson equation of state for the Kalina cycle was compared to the WATAM [21]. WATAM is a proprietary code developed by Exergy, Inc. founded by Kalina. WATAM provides better fit of the ammonia-water properties for the analysis of the new Kalina cycles being developed by Exergy, Inc.

Three new designs of the Kalina cycle for low-temperature geothermal resource were presented by Henry A. Mlcak [22]. KCS11 for 121 to 204°C while KCS34 (for combined power system) and KCS34g (small plant size) for 121°C are shown below in Figure 7. Both the KCS11 and KCS34 are designed with recuperators (for pre-heating of the fluid to the evaporator). The advantages of the three cycles as...
compared to the Organic Rankine Cycle (ORC) were mainly due to the ammonia-water mixture varying boiling point and condensing temperatures which closely resemble the working fluid.

3. Trends
A commercial demonstration of the 2MW Kalina Cycle System 34 (KCS34) using low-temperature geothermal energy at 121°C was installed in Husavik, Iceland and start up on July 16, 2000 [23]. The plant provides power and hot water for industrial use specifically heating and drying of hardwood. The cycle runs on an 82% ammonia-water mixture. Performance testing using ASME Performance Test Code practice was conducted and resulted with a net power output of 1,696kW and 1,719 kW. The plant has 90% reliability range over the initial 18 months operation.

The National Renewable Energy Laboratory (NREL) of the US developed a project with Exergy-AmeriCulture for a 1 Megawatt water-cooled Kalina-Cycle Plant (KCS34) located in Cotton City, New Mexico [24], [25]. The plant was designed to provide electrical power for a fish hatchery and to heat tilapia tanks of the hatchery on site. This provided a good example of integration of the Kalina cycle in the agribusiness sector using low-temperature geothermal resource as the heat source.

DiPippo [26] conducted second law assessment of the KCS34 installed at Husavik Island and different set-ups of binary plants for low-temperature geothermal resource to confirm the claims that it has 30-50% advantage over the ORC operating at the same heat source. The overall exergetic efficiency was used for the assessment.

Mirolli [27] presented an application of the Kalina cycle system for the use of the cement industry. The production of cement utilize a large amount of energy and the waste heat can be used for the generation of power using the KCS1-2 shown in Figure 8. The heat source temperature ranges from 200 to 400°C that can be used for the Kalina cycle and provide 20-40% efficiency range compare to the typical Steam cycle.

Koroneos and Rovas [28] studied the application of the Kalina cycle in the geothermal resource in Dodecanese, Greece. A vapor-water mixture with temperature of 187°C is flashed and the steam is expanded to a turbine to produce 935.50 kW power. The exhaust steam is then used as heat source of the Kalina cycle. The geothermal liquid and the Kalina cycle condenser exhaust is then used for a four stage desalination system to maximize the efficiency. Exergy method is used in the analysis and it was found that the addition of the desalination system provides 2% increase in exergetic efficiency of the system.

A workshop in Strasbourg, France in 2006 about electricity generation from Enhanced geothermal systems presented new generation of the Kalina cycle for geothermal applications [29]. System Geothermal New Generation SG 2a and SG2d were presented. SG2a (Figure 9) applies to resources with tempretures below and equal to 150°C while SG2d is for applications about 150°C.

The Kalina cycle combined with a single stage absorption chiller was analyzed to provide both power and cooling effect from the waste heat of the blast furnace at Kashima Steel industry in Japan. This combination of the said cycle and chiller is also known as a Load-leveling Hyper Energy Converting and Utilization System (LHECUS) and was simulated using the engineering equation solver or EES [30]. The simulation showed that the maximum overall efficiency (30%) was reached with the concentration is 0.89 and the separator temperature is at 45°C.

Nasruddin et al [31] conducted simulation using Cycle Tempo 5.0 to analyze the energy and exergy of the KCS34 used in Iceland. The KCS34 simulation used the Huvasik geothermal plant data in the simulation and determined the plausibility of using this cycle in Indonesia. It should be noted that the cooling water in Iceland is at 5°C while in Indonesia the water temperature ranges from 20-24°C with air temperature ranging from 18-24°C. Highest power output was found to be at 2.145 MW and maximum exergetic efficiency of 69% using concentration of 85.5% ammonia-water.

Ogriseck [32] simulated the Husavik Kalina cycle integrated in Industrie-park Hoechst plant in Germany using EBSILON® Professional, Version 7.01 Beta-release. The heat source is taken from the flue gas from the combine heat and power plant and ranges from 130-150°C. Cooling water in Germany is taken as 20°C as the 5°C temperature in Iceland is not attainable. The plant simulation produced 320-440kW and efficiency at 13.5-18.8%.
Figure 8: Typical Kalina Cycle for A cement Kiln [27]

Figure 9: SG2a for temperatures ≤ 150°C [29]

The combined Rankine-Kalina cycle was used as part of a novel Concentrating Solar Thermal Power (CSP) block specifically in a 50MW parabolic trough power system in Beer-Sheva, Israel [33]. The use of the Kalina cycle as the bottoming cycle for this system proved to be advantageous as heat storage can be utilized to run the Kalina cycle. The cycle is powered by the extracted steam from the Rankine cycle at 170°C during high insolation. During low insolation, heated oil from the solar panels is used for the operations of the Kalina cycle.

Arslan [34] conducted an exergoeconomic analysis of the KCS34 for medium-temperature geothermal resource available in the Simav geothermal field in Turkey where the temperature are observed to be at 148°C. The plant was found to generate 290-41.2 MW net power with 9.7 to 14.8% efficiency range. Evaluation of the exergy destruction resulted in the maximum destruction occurring in the Evaporator and pre-heater of the Kalina cycle.

The Republic of Croatia evaluated the Kalina cycle and the ORC for the geothermal resource present in the country [35]. ORC performed very well over the Kalina cycle with the geothermal resource temperature of 175°C with 15°C air cooling system. The advantage of the Kalina cycle over the ORC was realized in the lower temperature resource from 120-125°C and 108-122°C. Direct use of the geothermal water from the plant was also considered in the analysis. The ORC plant estimated power output is at 5270 kW (80.13 kg/s) while the Kalina only has 3949 kW power at 35.717 kg/s.

A competition for the appropriate power plant technology for the Chingshui Geothermal Field in Changhua County, Taiwan, pitted the ORC against the Kalina cycle for the available 120°C geothermal resources [36]. The Kalina cycle generated more power than the ORC. The former used an Euler turbine which is a radial outflow designed for energy recovery. Similarly, A 100kW plant was commissioned in a research laboratory in Shanghai, China for the study of the improvements of the Kalina cycle.

Japan was interested in developing a 50kW power plant for the hot spring in Matsunoyama field in Niigata Prefecture running on the Kalina cycle [37]. This plant will use the waste hot spring with temperatures of about 100°C and the cooled exhaust with then be used for the hot bath and also for space heating. Installation and generation testing of the 50kW Kalina plant in the Matsunoyama field concluded on December 2011 [38].
Ganesh and Srinivas [39] designed a kalina cycle with a solar collector with vacuum tubes for solar thermal power generation using conditions in India. It was summarized that the concentration at the turbine affects the high pressure but is not a factor for the low pressure.

In Brazil, a comparison between the ORC and Kalina cycle exergetic and economic performance for low geothermal applications used ASPEN-HYSYS in the evaluation [40]. The simulation used 90-140°C source temperature with dead state at 25°C. Working fluid for the ORC used 15 types of pure substances to determine the most appropriate for the power generation while 3 ammonia-water concentration were used for the Kalina cycle. Results showed that the Kalina cycle produced 18% more power and 17.8%.

Koroneos and Rovas [41] conducted exergy analysis of the Kalina cycle as a bottoming cycle of a high enthalpy geothermal plant in the Nisyros island in Dodecanese, Greece. The geothermal fluid for the Kalina cycle has a temperature of 120°C and 2 bar pressure and produces 932.5kW of water, the brine is then used for a desalination system with 4 stages. It was found that the desalination system provide 2% of the efficiency of the system.

Sec Singh and Kaushik optimized the Kalina cycle (KCS11) bottoming cycle used for a 67.5MW coal-fired steam power plant at Delhi, India using MATLAB [42]. The authors indicated that the maximum cycle efficiency is observed with an optimum ammonia concentration at a given inlet pressure at the turbine. The ammonia fraction is similar to the value used in the Husavik Kalina power plant in Iceland. Kenya is one of the countries blessed with geothermal resources. The simulation of Kalina cycle used for the medium geothermal resource of 120°C reached 20% efficiency but at high pressure and greatly affected the cost of the plant [43].

Gupta et al [44] simulated the Kalina cycle for low temperature geothermal resource available in India and applying the local conditions to determine the energy and exergy of the cycle. The turbine inlet ammonia concentration of 92% and turbine exit pressure of 7.5 bar generated the maximum power for the said cycle.

The Sweden steel industry uses a large amount of energy for the processes involved in integrated and secondary steelmaking. Johansson and Soderstrom [45] recommended the use of the Kalina cycle or ORC in the waste heat recovery of the steel making processes. Thermophotovoltaic (TPV) methods are suggested for heat recovery and can be used for running the Kalina and ORC to generate power.

Modi and Haglind [46] presented a study using the Kalina cycle for a central Solar Thermal Power Plant (STPP) in Denmark. The simulation involved two scenarios for the comparison of the Kalina cycle and Rankine cycle. First scenario involves direct steam generation where the heat input is the solar receiver only. For this scenario the Rankine cycle has a better performance than the Kalina. The second scenario is with use of a two-tank molten-salt storage. The Kalina cycle outperforms the Rankine cycle.

A study of a 500MW coal-fired thermal power plant coupled with the Kalina cycle to provide power for coal mill rejection in India indicates a minimum 5627.745 kW output [47]. Kalina cycle efficiency reaches 24.74% with 20 bar and 442.40K Turbine inlet pressure and temperature, respectively.

Iran also showed interest in the Solar-driven Kalina cycle as studies showed that solar energy resources can be developed in the central and southern parts[48]. The solar system using KCS11 can provide the needed annual demand for residential buildings in Hormozgan and Isfahan. The annual demand of the residential buildings in the two provinces can be provided by the Solar-Kalina cycle studied.

In Indonesia, The Wayang Windu geothermal power plant considered using the KCS11 as the bottoming cycle to maximize the brine that is coming out of the separator at 180°C [49]. The system simulation, using Peng-Robinson Method, produced 1734 kW of power at 13.20% efficiency.

In Italy, the ORI Martin Steel mill was installed with an ORC for such application. Milewski and Krasucki [50] compared the ORC to its alternative Kalina cycle and found that Kalina cycle can be effective and competitive to the installed ORC when the heat source temperature reached 200°C and above.

In the Brazil cement industry, the Kalina cycle has been considered for the waste heat recovery system of the rotary kiln cyclone preheater with gas temperature at 663.15K [51]. The Brazilian cement factory can produce 2,100 tons of clinker daily. The use of the Kalina cycle as the waste heat recovery system provides 2,429.056 kW with 23.3% and 47.8%, energy and exergy efficiencies, respectively.
Singh [52] applied the Kalina cycle as heat recovery system to a 16MW grid-connected bagasse-fired cogeneration plant of a sugar factory in India. 105°C heat source was used for the simulation using MATLAB. The cycle was able to generate 375.2135 kW from the cogeneration plant.

Ozahi and Tozlu [53] used the Kalina cycle for a 5.66 MW solid waste power plant in Turkey to recover power from the waste heat of the plant. The heat source is taken at 566 K with the Kalina cycle producing 954.6 kW of power at 24.15% efficiency.

There are no geothermal power plant in Poland but there is potential to generate power from low enthalpy geothermal resource available at 86°C [54]. ORC and Kalina cycle comparison was made to determine which technology will be appropriate for the said application. The results showed that the Kalina cycle provided 1.6 MW compared to the 900 kW of the ORC.

4. Conclusion
The Kalina cycle is a novel cycle which can be used for different industries as bottoming cycle, heat recovery system and stand-alone low-temperature power plant. The degree of freedom that the ammonia-water provides to the system is very valuable and understanding the appropriate conditions can yield better performance than the century-old steam cycle created by William Rankine. Possible studies in the properties of ammonia-water mixture in the supercritical and high-temperature ranges can also provide a better understanding of the Kalina cycle. Hybrid and combination cycles are now in trend for this emerging technology.

5. References
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