Assessment of Economic Impact and Efficiency of a Combined Gas Turbine with a Thermoelectric Generator

Onoroh Francis, Ikebudu Kingsley O., and Okafor I.O.U

Abstract– **The research presents how to scavenge waste heat from a gas turbine plant using a thermoelectric generator and to assess the economic implication. On comparing the equivalent uniform annual worth of the combined GT/TEG with GT only, the annual disbursement for the GT/TEG is $2,288,231.908 and for the GT only is $2,316,738.107. Therefore, the combined GT/TEG is found to be more economical. The gas turbine whose operating condition was used for the design of the thermoelectric generator is based at Ughelli Thermal power station, Ughelli, Delta state, Nigeria. Also, the efficiency of the gas turbine was increased from 0.342 to 0.453 with the introduction of a thermoelectric generator containing lead telluride modules.**

Keywords– Economic Analysis, Efficiency, Gas Turbine, Thermoelectric Generator, Sankey Diagram and Equivalent Uniform Annual Worth

I. INTRODUCTION

Increased overall plant efficiency is possible by coupling a thermoelectric generator to an existing gas turbine plant. A combined GT/TEG system is more economical than a GT only. One way to improve the sustainability of electricity base is through the scavenging of waste heat with thermoelectric generators i.e. thermoelectric materials.

Gas turbine exhaust, automotive exhaust, steam turbine and industrial processes all generate waste heat that could be converted to electricity using thermoelectric generator. Fig. 1 shows the Sankey diagram for most thermal engine plant. Up to 40% of the combustion energy supplied leaves in the exhaust. Furthermore, the exhaust temperature is much greater than that of the other heat rejection streams; therefore, the potential conversion efficiency of a bottoming cycle connected to this stream is expected to be the largest.

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As thermoelectric generators are solid-state devices with no moving parts, they are silent, reliable and scalable, making them ideal for distributed power generation.

The efficiency with which thermoelectric materials generate energy is determined by the thermoelectric figure of merit, ZT, where T is absolute temperature and Z is proportional to the electrical conductivity and the square of the Seebeck co-efficient, and inversely proportional to the thermal conductivity. When ZT increases, the efficiency of energy generation ultimately approaches the Carnot limit, i.e. the maximum allowed by the laws of Thermodynamics.

Historically, the ZT value of the best bulk thermoelectric materials have remained below or around one due to the difficulty of increasing the electrical conductivity or Seebeck co-efficient without increasing the thermal conductivity [1].

However, ZT values approaching three have been reported for nanostructured materials that exploit reduced dimensionality to lower the thermal conductivity of the crystal lattice in these structures. ZT values of three or more are required for competitive energy generation [1].

II. BASIC THERMOELECTRICITY

A. The thermoelectric phenomena

The three basic thermoelectric effects are the Seebeck effect, the Peltier effect, and the Thomson effect. These effects underlie the conversion of heat energy into electrical energy or vice versa. When a steady temperature gradient is maintained along a finite conductor, the free carriers at the hot end will have greater kinetic energy and tend to diffuse to the cold end. The accumulation of charge results in a back

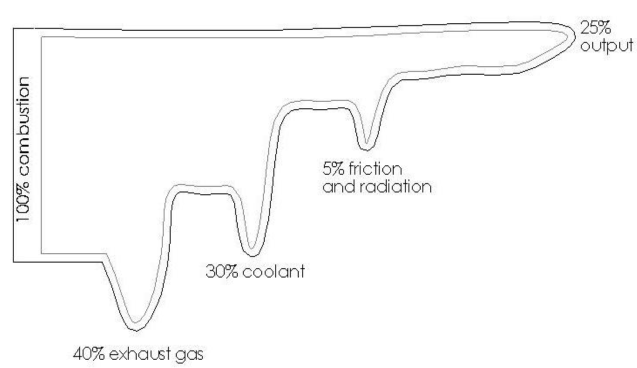

Fig. 1. Sankey diagram for Power plant

electromotive force (e.m.f) which opposes a further flow of charge. The Seebeck voltage is the open circuit voltage when no current flows. If the junction of two dissimilar conductors are maintained at two different temperatures T_1 and T_0; where $T_1 > T_0$; an open circuit potential difference is developed:

$$V_o = \alpha_{p,n} \left(T_1 - T_o\right) \quad (1)$$

Where $\alpha_{p,n}$ is the Seebeck coefficient.

The Seebeck coefficient of the junction between two materials p and n is the same as the difference between the two absolute coefficients [3]:

$$\alpha_{p,n} = \alpha_p - \alpha_n \quad (2)$$

Thermocouples formed from two dissimilar conductors are used to measure temperature by thermoelectric generation of electricity from heat. Metal alloy thermocouples are also in use. Most metals possess Seebeck coefficients of 10 μV/K

or less, but semiconductor materials are promising in constructing the thermocouples because they have Seebeck coefficients in excess of 100 μV/K.

Good thermoelectric materials must have large Seebeck coefficients, high electrical conductivities and low thermal conductivities to retain the heat at the junction and to reduce the heat transfer losses.

These requirements are summarized in what is called the figure of merit Z [4]:

$$Z = \frac{\alpha^2 \sigma}{\lambda} \quad (3)$$

where α is the Seebeck coefficient, σ the electrical conductivity, and λ the thermal conductivity.

In the late 1950s realization that devices based upon the thermoelectric effect could have possible military applications [5], [6] resulted in a tremendous experimental survey of semiconductor materials which led to the discovery of some semiconductor materials having Z-values higher than metals or metal alloys.

Recently, research in thermoelectricity aims to obtain new improved materials for autonomous sources of electrical power in specialized medical, terrestrial and space applications and to obtain an unconventional energy source after the oil crises of 1974 [7], [8]. Large-scale thermoelectric generation of electricity requires the production of substantial amounts of semiconductor materials, accompanied by a significant improvement in the material figure of merit.

B. Theory of Thermoelectric Power Generator

A thermoelectric power generator consists of many thermocouples. A thermocouple produces low voltage and high current. Thus, to obtain high voltages, a number of thermocouples are connected electrically in series and thermally in parallel to form a module. The module is heated at one end (hot side) and a temperature gradient was maintained with respect to the other end (cold side).

Thermoelectric Generators using the Seebeck Effect basically work on a temperature differential. The greater the differential of the hot side less the cold side, the greater the amount of power that will be produced.

For any thermoelectric power generator (TEG), the voltage(V) generated by the TEG is directly proportional to the number of couples (N) and the temperature difference between the top and bottom sides of the TE generator and the Seebeck coefficients of the n and p- type materials.

C. Materials

Several materials have been developed, according to Bulusu et al [9], the first thermoelectric materials were metals, but in the middle of the 20th century semi-conductors were noticed by Loffe [4] due to their high Seebeck coefficient and because heat conduction is dominated by phonon transport. Positive feature in metals is relatively high ratio of electrical to thermal conductivities. However, modern thermoelectric materials are essentially semi conductors.

It was later in 1909 [10] and 1911 [11] that Altenkirch showed that good thermoelectric materials should possess large Seebeck coefficients, high electrical conductivity and low thermal conductivity. A high electrical conductivity is necessary to minimize Joule heating, while a low thermal conductivity helps to retain heat at the junctions and maintain a large temperature gradient.

Bismuth telluride (Bi_2Te_3) and its alloys are good thermoelectric materials below room temperature. Above room temperature the relatively narrow band gap causes mixed conduction due to both electrons and holes, this leads to reduced Seebeck coefficient [1]. Bismuth telluride can be alloyed with Antimony telluride (Sb_2Te_3) or Bismuth Selenium (Bi_2Se_3) which reduces thermal conductivity considerably. Pseudo-ternary system of $B_{i2}Te_3$ – Sb_2Te_3 – Sb_2Se_3 has also been formed [9].

PbTe has high mean atomic weight and a multi-valley band structure, the band gap at 300k is 0.32eV [1] which produces higher Seebeck effect than that of Bismuth telluride. Its thermoelectric figure of merit (ZT) is also higher when the temperature is raised although it has better lattice thermal conductivity than bismuth telluride [9].

PbTe – SuTe system has been studied since 1961. Lead Telluride forms

isomorphous solid solution with Lead Selenide and tin telluride, which leads to lower thermal conductivity and improved ZT values [1].

Silicon-Germanium (SiGe) alloys are good materials for thermoelectric generation [9]. Silicon has a large bandgap and therefore Silicon rich alloys such as $Si_{0.7}$ $Ge_{0.3}$, are suitable for high temperature applications because problems with minority carrier dominance do not arise. The large phonon scattering ensures low thermal conductivity without affecting the electron mobility [9].

Skutterudites ($ReTm_4M_{12}$) are complex materials containing rare earth elements (R_e), transition metals (T_m) and metalloids (M). Binary skutterudites have chemical formula of T_mM_3 and relatively high thermal conductivity, but the Seebeck coefficient is also relatively large. The crystal structure of binary skutterudites has two large empty spaces in each unit cell.

D. Thermoelectric Generator Combined Plant

Fig. 2 shows the schematics of thermoelectric generator and gas turbine plant. Here the exhaust from the gas turbine flows into the thermoelectric generator; the exhaust exits through the chimney after the supply of the quantity of heat required to maintain the thermolegs at maximum temperature. The cooling oil after exchanging heat with water in the oil/H_20 heat exchanger is also passed through the thermoelectric generator maintaining the themolegs at the minimum temperature. The cooling oil from the gas turbine and thermoelectric generator is then recycled by cooling with the oil/H_2O heat exchanger.

The output voltage of the thermoelectric generator being D.C is feed into the power conditioning unit (P.C.U), the P.C.U converts the DC voltage to A.C voltage to ensure synchronization with the gas turbine alternator output, before being fed into step-up transformer and subsequent transmission.

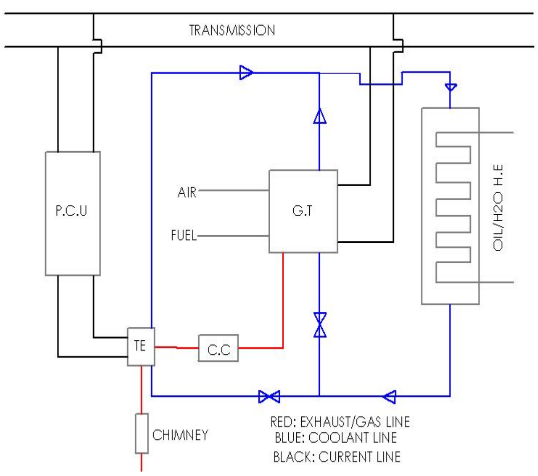

Fig. 2. Thermoelectric generator combined plant

P.C.U Power Conditioning Unit
C.C Catalytic Converter
T.E Thermoelectric Generator
G.T Gas Turbine

III. ENGINEERING ECONOMICS ANALYSIS

Its deals with the concepts and techniques of analysis useful in evaluating the worth of systems, products and services in relation to cost.

It is used to answer many different types of question like

- Which engineering projects are worthwhile
- Which engineering projects should have a higher priority
- How should the engineering projects be designed

It basic concepts involves cash flow, interest rate and time value of money, equivalent technique [12].

The three commonly used economic analysis method are [12]:

- Present worth analysis
- Annual worth analysis
- Rate of return analysis

The equivalent uniform annual worth is a method commonly used for comparing alternatives, its means that all incomes and disbursements (irregular and uniform) must be converted into equivalent uniform annual amount (that is an end of period amount which is the same each period) [12].

Since the thermoelectric generator produces additional power for the same gas flow rate, comparison of the cost of producing the total output with gas turbine/thermoelectric generator (GT/TEG) and with the gas turbine (GT) only was carried out on the basis of equivalent uniform annual worth (EUAW).

IV. METHODOLOGY

The research focused on a gas turbine bottomed with a thermoelectric converter that will effectively tap some of the energy of the flue gas and thus convert it into useful power which can be fed into the national grid. The gas turbine plant whose operating conditions were used for the design is the Ughelli-Thermal Station (Delta IV) in Delta State.

The operating parameters of the gas turbine are [13]:

Turbine alternator output power =	25MW
Alternator current =	1100A
Alternator output voltage =	11KV
Alternator frequency =	50HZ
Efficiency of the gas turbine =	0.342
Alternator speed =	7280rpm
Gas turbine inlet temperature =	$1200^{O}C$
Exhaust gas temperature =	$520^{O}C$
Gas turbine inlet pressure =	1.4MPa
Turbine type =	Axial
Turbine stages =	3
Compressor stages =	17
Cooling oil inlet temperature =	$59^{O}C$

The technical steps taken involves firstly the collection of data at the plant site, notably the exhaust gas temperature exiting the gas turbine which acts as the source temperature to the thermoelectric generator and the coolant temperature of the gas turbine which acts as the sink temperature to the thermoelectric generator.

Secondly, based on the magnitude of the exhaust temperature of the gas turbine, a suitable thermoelectric material was selected from a catalog of materials; the exit exhaust temperature favours Lead Telluride (PbTe) [2].

Thirdly, the thermoelectric generator was then design from the operating conditions of the gas turbine, the major components being sized.

The operating conditions of the plant relevant to the design of the thermoelectric generator are:

Turbine alternator output =	25MW
Alternator current =	523A
Alternator frequency =	50Hz
Exhaust gas temperature =	$520^{O}C$
Cooling oil inlet temperature =	$59^{O}C$
Efficiency of gas turbine plant =	0.342

The thermoelectric generator performance was simulated to depict how the efficiency of the thermoelectric generator varies with different sink temperature.

Finally, comparison between the two alternatives was done on the basis of equivalent uniform annual worth.

V. DESIGN OF THERMOELECTRIC GENERATOR

Parameters used for design

Seebeck coefficient (α) =	628μV/K
Figure of merit (ZT) =	1.5
Temperature range for operation =	300-800K
Thermal conductivity (k) =	1.11W/cmK
Current density (Id) =	$6A/cm^2$
Resistivity =	0.011Ωcm

The components to be designed are the quantity of heat to be supplied and rejected to the thermoelectric module through the heat exchangers and the voltage per module.

A. Heat Input by the Exhaust Heat Exchanger

The quantity of heat supplied the flue gas is defined as [7]:

$$Q_1 = \alpha_{p,n} I T_1 - \frac{1}{2}\left(\rho_{p,n}\frac{L}{A} I^2\right) + k_{p,n}\frac{A}{L}(T_1 - T_O) \tag{4}$$

The capacity of the exhaust Heat exchanger to be installed is at least 9.2KW.

B. Heat Rejected By the Coolant Heat Exchanger

The heat to be carried away by the cooling oil is defined as [7]:

$$Q_2 = \alpha_{p,n} I T_O + \frac{1}{2}\left(\rho_{p,n}\frac{L}{A}\right) I^2 + \left(Kp,n\frac{A}{L}\right)(T_1 - T_O) \tag{5}$$

The capacity of the coolant heat exchanger to be installed is at least 8.776KW.

C. Voltage Per Module

The voltage generated per module is defined as [7]:

$$V_L = \alpha_{p,n}(T_1 - T_o)\left(\frac{\sqrt{1+ZT}}{1+\sqrt{1+ZT}}\right) \tag{6}$$

A voltage of 0.1773V is obtained per module.

D. Power Output per Module

The power obtained per module is obtained from [7]:

$$P = \frac{\sqrt{1+ZT}}{\left(1+\sqrt{1+ZT}\right)^2} \times \frac{\alpha_{p,n}^2 (T_1 - T_O)^2}{\rho_{p,n}\frac{L}{A}} \tag{7}$$

Power output of 32.2W is obtained per module.

E. Efficiency of the Thermoelectric Generator

The efficiency of the thermoelectric generator is obtained from:

$$\eta_{TEG} = \frac{T_1 - T_O}{T_1}\left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_O}{T_1}}\right) \tag{8}$$

A figure of 0.169 is obtained.

VI. RESULTS

The efficiency of the thermoelectric generator is determined by [7]:

$$\eta_{TEG} = \frac{T_1 - T_O}{T_1}\left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_O}{T_1}}\right) \tag{9}$$

Fig. 3 shows the efficiency curve against temperature difference.

The curves reveal that the increase in efficiency of the curves occurs primarily because the effective Seebeck coefficient of lead telluride modules decreases with increasing temperature difference for a constant cold side temperature, and the efficiency of the module depends upon the square of the Seebeck coefficient.

The curves reveal that the efficiency increases as the sink temperature decreases.

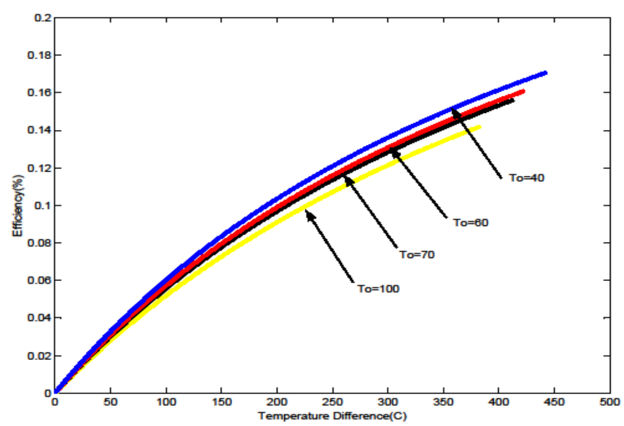

Fig. 3. Thermoelectric module efficiency curves

By dividing top and bottom by T_1 in equation 4.25, the efficiency of the thermoelectric generator can be expressed as:

$$\eta_{TEG} = \left(1 - \frac{T_0}{T_1}\right)\left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_O}{T_1}}\right) \tag{10}$$

Fig. 4 shows a plot of efficiency against sink – source temperature ratio obtained from Fig. 3. As expected the curves collapsed into one curve. Also plotted on Fig. 4 is the Carnot cycle efficiency curve for the purpose of comparison.

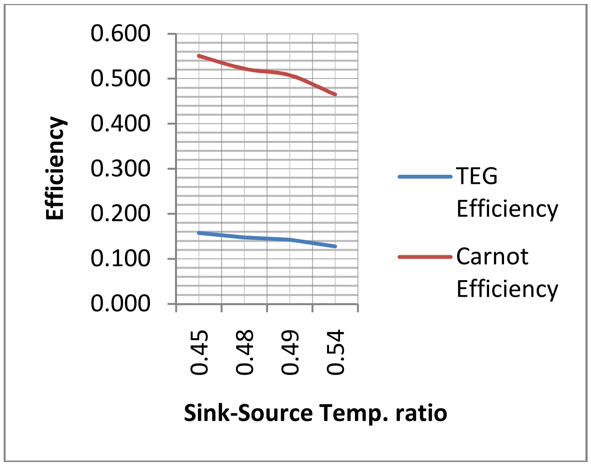

Fig. 4. plot of efficiency against sink-source temperature ratio

The Carnot efficiency is defined by:

$$\eta_{Carnot} = 1 - \frac{T_0}{T_1} \quad (11)$$

The overall combined efficiency of the plant with thermoelectric generator installed is determined by [14]:

$$\eta_{comb} = \eta_{GT} + (1 - \eta_{GT})\eta_{TEG} \quad (12)$$

A figure of 0.453 is obtained. This is a substantial improvement in the efficiency of the gas turbine plant.

VII. ECONOMIC ANALYSIS

Since the thermoelectric generator produces additional power for the same gas flow rate, comparison of the cost of producing the total output with gas turbine/thermoelectric generator (GT/TEG) and with the gas turbine (GT) only was carried out on the basis of equivalent uniform annual worth (EUAW).

The cost implications for the gas turbine (GT) only in operation are:

Initial cost of investment = $16828125
Operation and maintenance cost = $531562.5
Salvage value = $1270181.25
Life of equipment = 20years
Minimum attractive rate of return (MARR) = 8.75%

Fig. 5 shows the corresponding cash flow diagram.

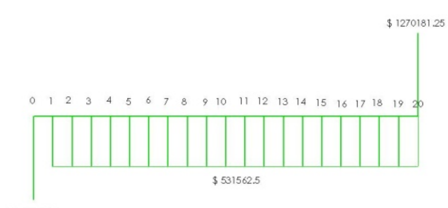

Fig. 5. Cash flow diagram GT only

The cost implications for the combined mode of operation of the GT/TEG are:

Initial cost of Investment = $16936101.2
Operation and maintenance cost = $492187.5
Salvage value = $1307467.01
Life of equipment = 20years
Minimum attractive rate of return (MARR) 8.75 %

Fig. 6 shows the corresponding cash flow diagram.

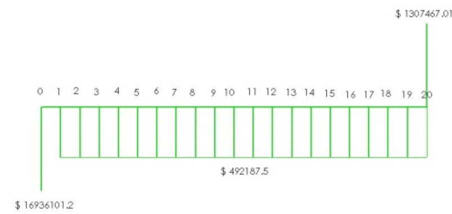

Fig. 6. Cash flow diagram for GT/TEG

From Fig. 5, the equivalent uniform annual worth of the gas turbine (GT) only is computed as:

$EUAW_{GT}$ = -16828125 (A/P, 8.75%, 20) – 531562.5+1270181.25 (A/F, 8.75%, 20) = -16828125x0.1076 –531562.5+ 1270181.25 x 0.02010 = -2,316,738.107

From Fig. 6, the equivalent uniform annual worth of the gas turbine-thermoelectric generator (GT/TEG) combine mode is computed as:

$EUAW_{GT/TEG}$ = -16936101.2 (A/P, 8.75%, 20) – 492187.5+ 1307467.01 (A/F 8.75%, 20) = -16936101.2x0.1076– 492187.5 + 209194722.1x0.02010 =-2,288,231.908

Comparing both equivalent uniform annual worth, the annual disbursement of the combined mode of operation of the GT/TEG is small compared to the GT only i.e. $EUAW_{GT/TEG} < EUAW_{GT}$, though the percentage increment is small (1.24%), the combined GT/TEG is preferred due to its higher efficiency and stand recommended. The income from the sale of the power generated was not considered in the analysis.

VIII. CONCLUSION

A high powered thermoelectric generator to provide additional electric power for a gas turbine is feasible, thus a thermoelectric generator system was designed from the operating conditions of a gas turbine. The choice is made of lead telluride as the thermoelectric module because of the temperature involved and its high dimensionless figure of merit (ZT).

The sensitivity to the coolant temperature is especially high because the thermoelectric efficiency increases with decreasing cold side temperature.

The efficiency of the gas turbine was considerably increased to 0.453 from 0.342, an increase in efficiency of 32.46%.

Economic analysis reveals that the project is feasible when compared with the gas turbine only in operation.

IX. RECOMMENDATION

Experimental testing will be an important phase of the project. It will show the effect of the thermoelectric generator on different systems of the gas turbine plant and will validate the result obtained. Considering the energy crisis in the country and the large number of existing gas turbines, more research still has to be done, a physical hardware built for experimental purposes before commercialization.

Appendix:

SYMBOLS AND MEANING

Symbols	Meaning	Unit
ZT	Dimensionless figure of merit	-
□$_{comb}$	Overall efficiency of plant	%
□$_{TEG}$	Efficiency of thermoelectric generator	%
Q_O	Heat rejected from the module	W
Q_1	Heat supplied to the module	W
I_d	Current density	A/cm^2
□	Resistivity	Ωcm
T_1	Source temperature	°C
T_0	Sink temperature	°C
$L_{p,n}$	Length of module	Cm
$A_{p,n}$	Cross sectional area of module	Cm^2
$K_{p,n}$	Thermal conductivity of module	W/cmK
$\alpha_{p,n}$	Seebeck coefficient of module	MV/K
V_L	Voltage per module	V
N	Number of module	-
P	Power	W
□$_{GT}$	Gas turbine efficiency	%
□$_{Carnot}$	Carnot efficiency	%

DATA FOR EFFICIENCY

S/N	ΔT	$\eta_{40}{}^{O}{}_{C}$	$\eta_{60}{}^{O}{}_{C}$	$\eta_{70}{}^{O}{}_{C}$	$\eta_{100}{}^{O}{}_{C}$
1	0	0.0000	0.0000	0.0000	0.0000
2	50	0.03276	0.0310	0.0301	0.0279
3	100	0.0602	0.0571	0.0557	0.0578
4	150	0.0834	0.0795	0.0777	0.0726
5	200	0.1034	0.0989	0.0967	0.0909
6	250	0.1207	0.1158	0.1134	0.1070
7	300	0.1360	0.1307	0.1282	0.1213
8	350	0.1494	0.1440	0.1414	0.1341
9	400	0.1614	0.1558	0.1531	0.1457
10	450	0.1721	0.1665	0.1638	0.1562
11	500	0.1818	0.1761	0.1734	0.1657

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