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Recovering the Waste Energy from the Electron-Ion Collider Cooling Water Systems

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Electron-Ion Collider

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DISCLAIMER

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A	12/26/22	Initial draft	R Srinivasan		
1	04/03/23	Edits and reviews	R Srinivasan	T Vijaya Kumar	C Folz

1 Introduction

While only a fraction of the electricity required for the EIC goes into the collision itself, most of the energy ultimately ends up being rejected to the environment via the infrastructure cooling systems. The energy utilized by the RF amplifiers, power supplies, magnets, vacuum systems, and cryogenics systems is rejected to the cooling towers that ultimately dissipate the energy to the atmosphere. Current estimates indicate approximately 50 MW of heat is dissipated at a low temperature by the cooling towers. A simplified energy balance is shown in Figure 1 below.

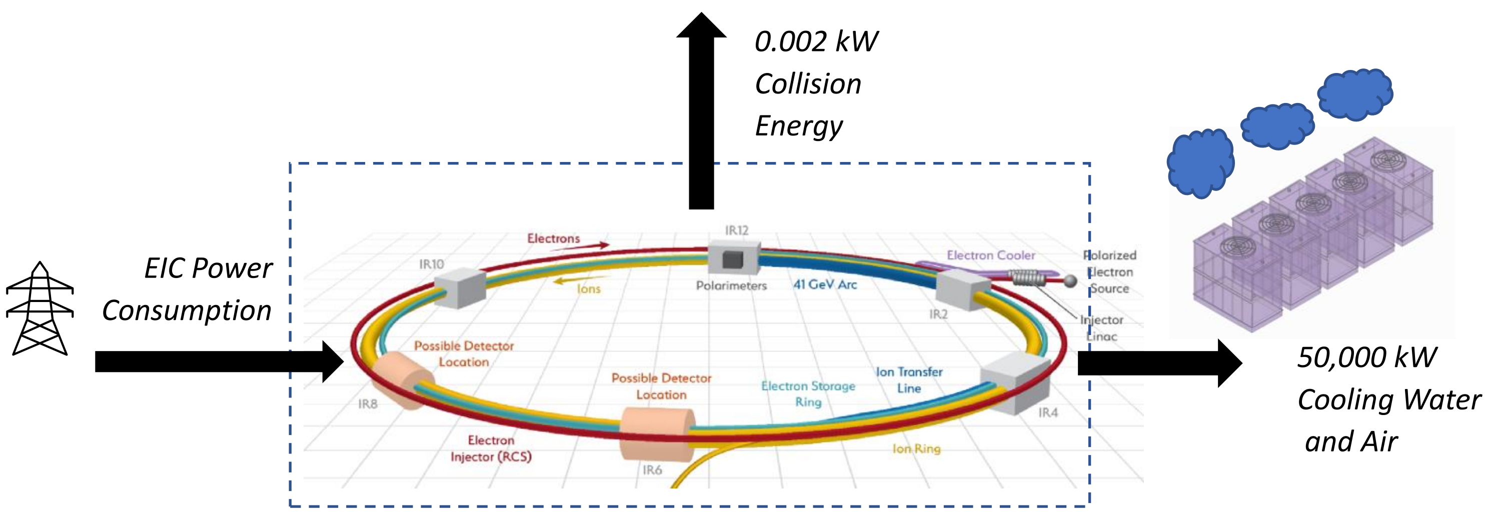


Figure 1 First Law Energy Balance Around the EIC

This technical note is prepared to conceptually demonstrate that feasible options exist to recover the low-temperature energy from the EIC cooling water systems.

2 Analysis

2.1 Analyzing the cooling water loads and temperatures.

The EIC Infrastructure group utilizes a requirements spreadsheet to collect cooling water parameters for the design of the EIC cooling tower systems. A listing of the components and heat loads by system is shown in Table 1.

Table 1 EIC Components that reject heat to water

Row Labels	Sum of Cooling Water (CW) Heat Load, kW	Count of Equipment Description
Beam Dumps	600	10
Cryogenics (Cryo)	2,707	131
HR Injection Upgrade Magnet	43	17
IR Normal Conducting Magnet	257	117
Power Supplies	2,550	468
Pre-injector (P-Inj)	136	46
RF Systems	27,615	855
Storage Ring Magnets (SR Mag)	4,215	1,526
Transfer Line Magnets (RCS To ESR)	63	30
Vacuum (Vac)	10,721	290
Grand Total	**48,906**	**3,490**

There are projected to be over 3000 components that reject heat to the cooling water system of which the large heat loads include the heat rejected in the vacuum systems due to the synchrotron radiation, the heat rejected by the RF amplifiers circulators and absorbers, the heat rejected by the normal conducting magnets used in the storage ring and the heat rejected by to the oil coolers by the helium compressors.

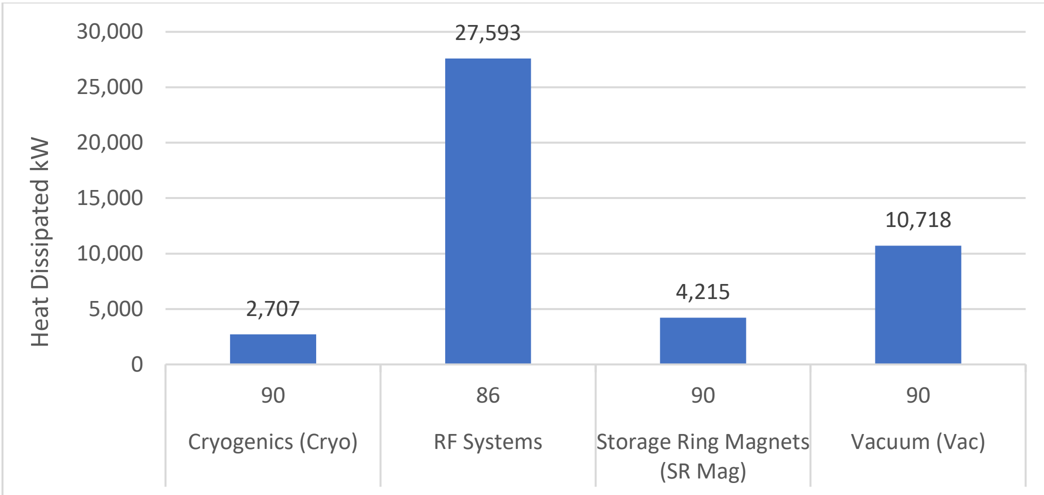


Figure 2 Large cooling water heat loads for EIC

An analysis of the large cooling loads (Figure 2) indicates that the heat is rejected at a temperature range of 86 to 96 Deg. F. The water cooled loads were in the process of being developed at the time of this evaluation and a nominal load of 50 MW was used for the study.

2.2 Conventional options for recovering low temperature energy: Carnot Cycle

To evaluate the feasibility of conventional heat recovery, we look at the Carnot potential for the ability to do work:

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}} = Carnot\ Efficiency$$

where T_{hot} is the heat rejected by the accelerator component that requires cooling (96F) and T_{cold} is the temperature from the cooling tower.

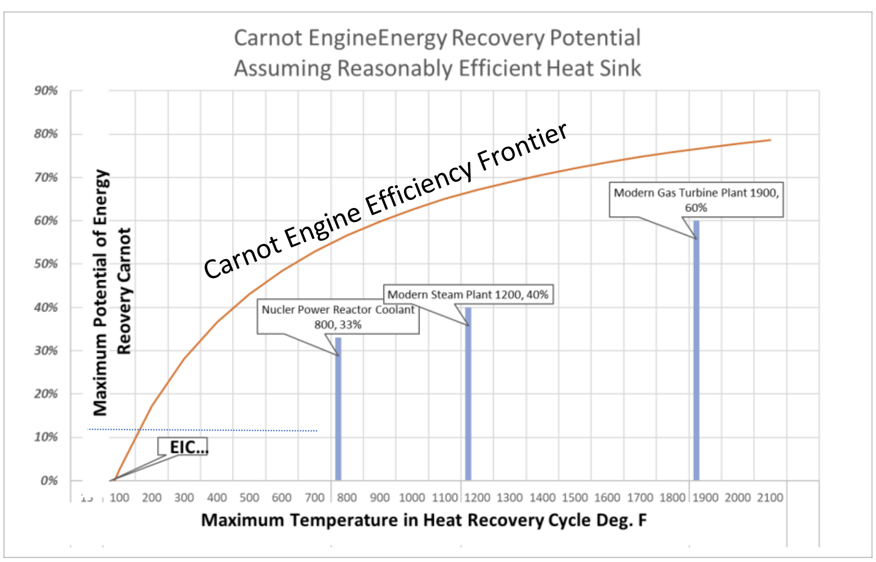


Figure 3 Low Grade Heat Recovery Potential of Cooling Water using Carnot Engine

The figure above is a comparison of the potential to recover energy using a theoretical Carnot Engine at different temperatures. Most power generation technologies operate at temperatures higher than 600 to 800 F where the potential for energy recovery ranges between 33% for a conventional steam plant all the way to 60% for a state of the art modern combined cycle power plant. The EIC water being rejected at 96F has a virtually non-existent potential to recover the energy via a Carnot Cycle Heat Engine and hence other means should be explored for the potential of low temperature heat recovery.

2.2.1 Other Options and Sources of Relatively Higher-Grade Heat

Beam Dumps for The Strong Hadron Cooling Heat Recovery LINACs

The energy recovery LINAC (ERL) includes an electron beam dump where electron bunches end up while depositing energy unrecovered by the ERL. The electrons are stopped in solid materials which will be cooled by water. It is estimated that this beam dump will dissipate 600 kW of energy continuously during operation. There may be a possibility to utilize high-pressure water to recover some of the 600 kW energy. For example, the main beam dumps for the linear collider utilize high pressure water to cool the water without evaporation. (Reference 8). Such a system can achieve high temperatures where a Carnot Engine option could be investigated. However, the complexity of the system and potential for water activation may preclude the feasibility of economically recovering a portion of the 600 kW.

Heat Recovery from the Cryogenics Compressor Oil Cooler

The oil coolers for the Helium compressors associated with the Cryogenics system can achieve temperatures as high as 150 Deg. F. However, since the building heating is at 150 Deg. F, it would require extensive modifications to recover a smaller fraction of the 2 MW of heat dissipated from the Cryo plant. Note that the average heat exchange occurs at the average of the supply and return hot water.

2.2.2 Evaluating the Feasibility of utilizing heat pumps for Building Heating at the Lab

During a recent benchmarking trip to the European Spallation Source in Sweden, it was noted that the facility extracts waste heat utilizing an advanced heat pump district heating program.

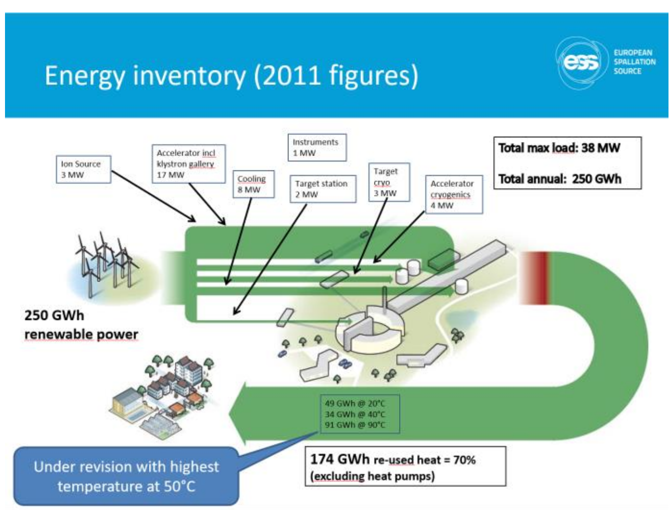


Figure 4 R. Garoby, ESS Courtesy Charlie Folz Director EIC Infrastructure - October visit to ESS & Max IV

Heat pumps utilize low-grade heat and convert to high-grade heat with the utilizing a compressor to pump the heat. Assuming that there is a local user available for utilization of the heat sink, we investigated the potential for heat recovery.

The concept would be to evaluate the heat from the EIC and utilize it locally. The low temperature heat from the EIC would need to be cooled via a cooling tower during normal operation. This heat is ultimately dischared to the atmosphere. If in such a configuration a heat pump is utilized, the low temperature cooling water heat at 94 Deg. F can be converted to high temperature water at 150 Deg. F for building heating. The thermal concept of such a system is shown in the figure below.

The cooling water inlet and outlet temperatures represent the low-grade heat source where assuming we were to transfer the heat from a 84F temperature to a temperature suitable for 150 Deg. F building hot water, we would require a heat pump. The difference between the temperature is called the temperature lift.

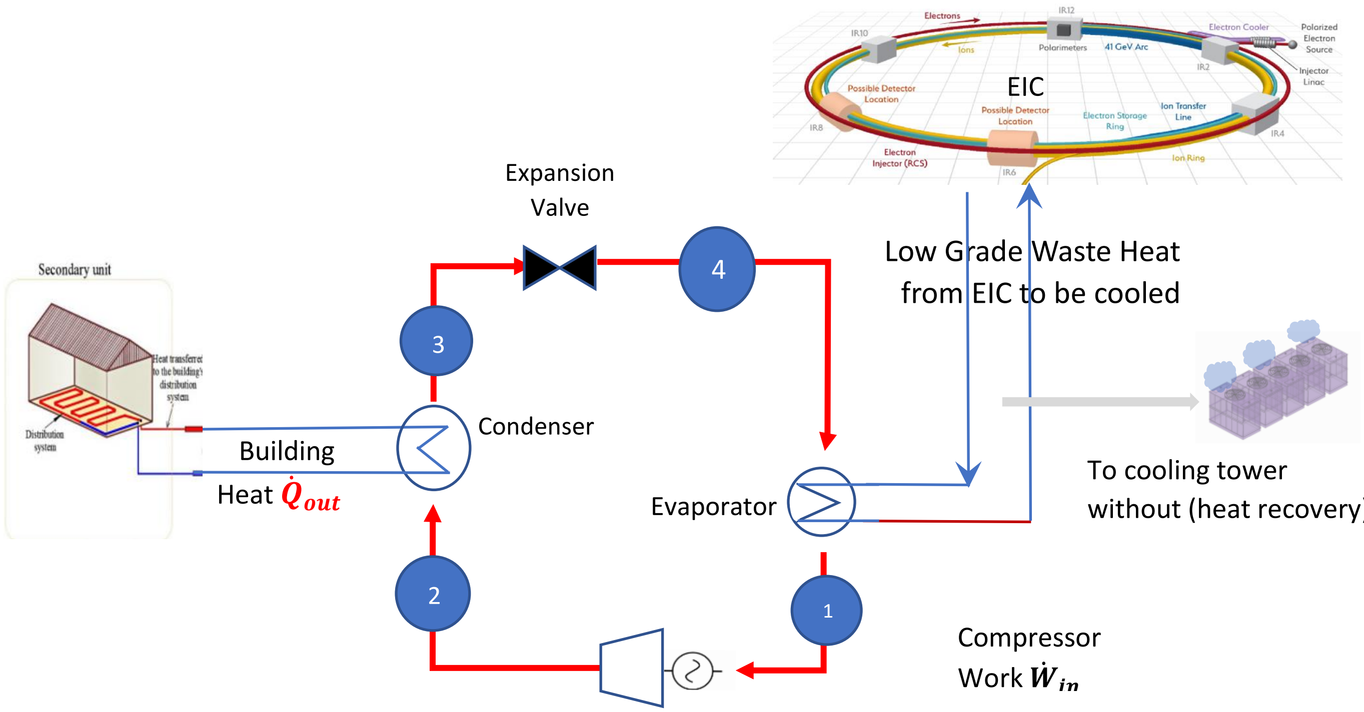


Figure 5 Thermal Schematic of Heat Recovery with Heat Pump

2.2.3 Estimating Performance and Savings with Refrigerant Compression Heat Pumps

To estimate the savings with a refrigerant compression heat pump we can determine the relationship between work input, temperature lift, and heat output using a parameter known as the heat pump coefficient of performance.

$$COP_{HP} = Q_{out}/W_{in}$$

In this equation, Q_{out} is the heat delivered by the heat pump and W_{in} is the energy or "work" supplied to the compressor. This is related to the temperature lift as follows,

$$COP_{HP} = Q_{out}/W_{in}$$

Analyzing Energy Recovery Efficiency with Ideal Carnot Cycle Heat Pump

For an ideal Carnot Cycle Heat pump the Coefficient of performance is given by

$$COP_{Carnot} = \frac{T_{out}}{T_{out} - T_{in}}$$

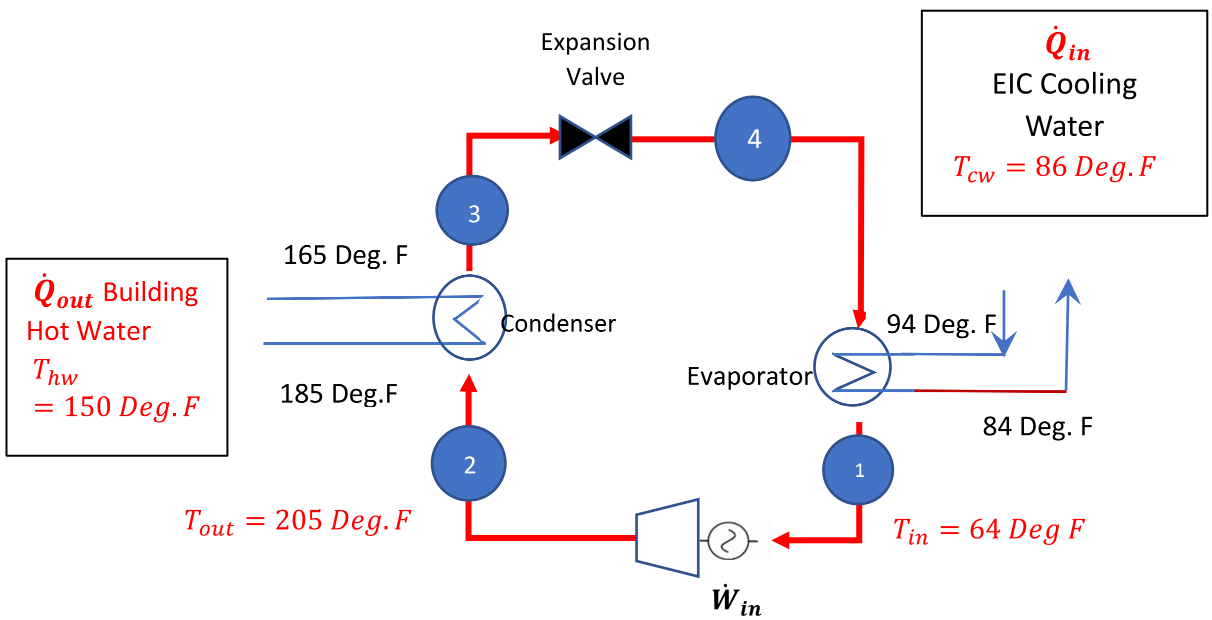


Figure 6 Heat Pump Schematic with Process Conditions

Here, T_{out} and T_{in} are the temperatures at which the heat pump delivers heat at the condenser and receives heat at the evaporator, respectively. Note that these are not the process stream temperatures which must be determined and related to the evaporator and condenser temperature of the refrigerant in the heat pump.

Ideally, for an 84 F EIC cooling water temperature and 150 Deg. F building hot water temperature,

$$COP_{Carnot} = \frac{T_{out}}{T_{out} - T_{in}} = 9.5$$

The amount of energy saved can be defined as the energy required for building heating minus the energy used for the temperature lift.

$$Q_{saved} = Q_{required} - W_{in}$$

Dividing both sides by the energy required, we get the percentage in energy savings.

$$\%\, Q_{saved} = 1 - \frac{1}{COP}$$

Utilizing a Carnot heat pump with a COP of 9.5, building that utilizes conventional heating can reduce the required energy consumption by 89%, which translates to an 89% reduction in fossil fuel energy input and an 89% reduction in associated heat emissions while delivering the same amount of heat.

Analyzing Energy Recovery Efficiency with Realistic Heat Pump Cycles

From the previous expressions, T_{out} is the maximum temperature in the refrigerant cycle. This is higher than the process heating stream temperature. The difference is based on the heat exchanger effectiveness of the refrigerant condenser and process supply hot water. The process supply hot water in turn has finite effectiveness that requires it to be above the building heating hot water temperature (T_{HW}).

Assuming an aggregate temperature differential of 20 Deg. F for the overall heat exchange process, the temperature can be determined as follows:

$$T_{out} = T_{HW} + T_{approach} = 170\ Deg. F$$

Similarly, T_{in} is the minimum temperature in the refrigerant cycle and has to be lower than the process cooling stream based on a finite efficiency of the boiling heat transfer process, also known as the evaporator pinchpoint temperature difference.

For the EIC at 86F maximum CW supply temperature (T_{CW}), and a heat exchanger pinch and approach temperature difference of 20 Deg.F for the overall heat exchange process, the temperature can be determined as follows:

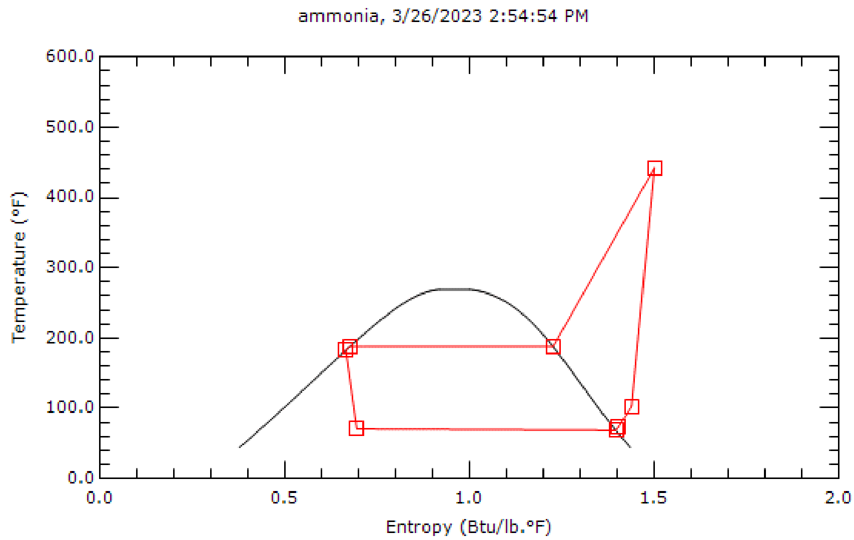
$$T_{in} = T_{CW} - T_{pinch} = 66\ Deg. F$$

So effectively, the fluid has to operate between 66 Deg. F and 170 Deg. F, resulting in a coefficient of performance for a system with reasonable effectiveness for the heat exchange process efficiency as

$$COP_{Carnot} = \frac{T_{out}}{T_{out} - T_{in}} = 6$$

This is still an ideal cycle in all other respects, assuming an ideal refrigerant can be found to operate within these temperatures.

To be able to determine a realistic COP for an actual heat pump that operates under these conditions, a cycle analysis was performed utilizing ammonia as a working fluid based on the methods in Reference 6. Looking at the temperature-entropy and pressure-enthalpy diagrams, a discharge pressure of around 700 psi is required in the operating range of the refrigerant fluid. The saturated cycle at this pressure is at 200 Deg. F.



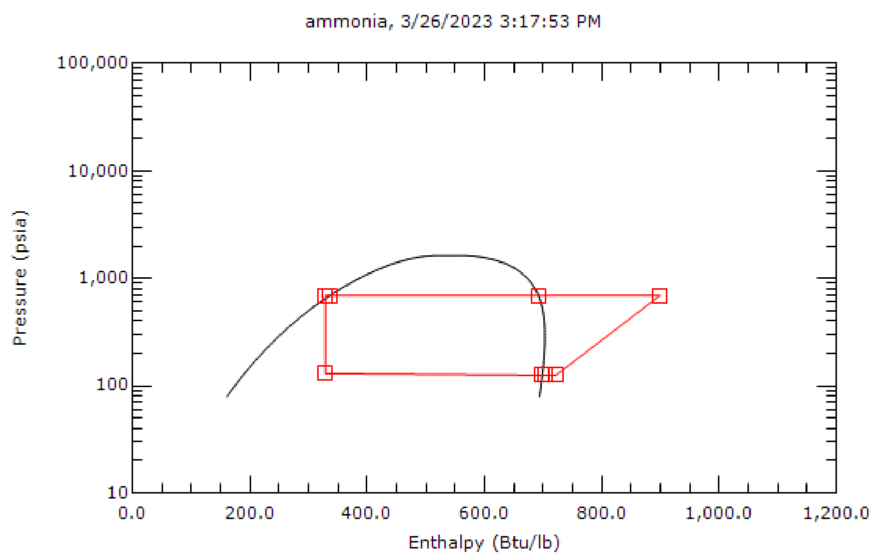
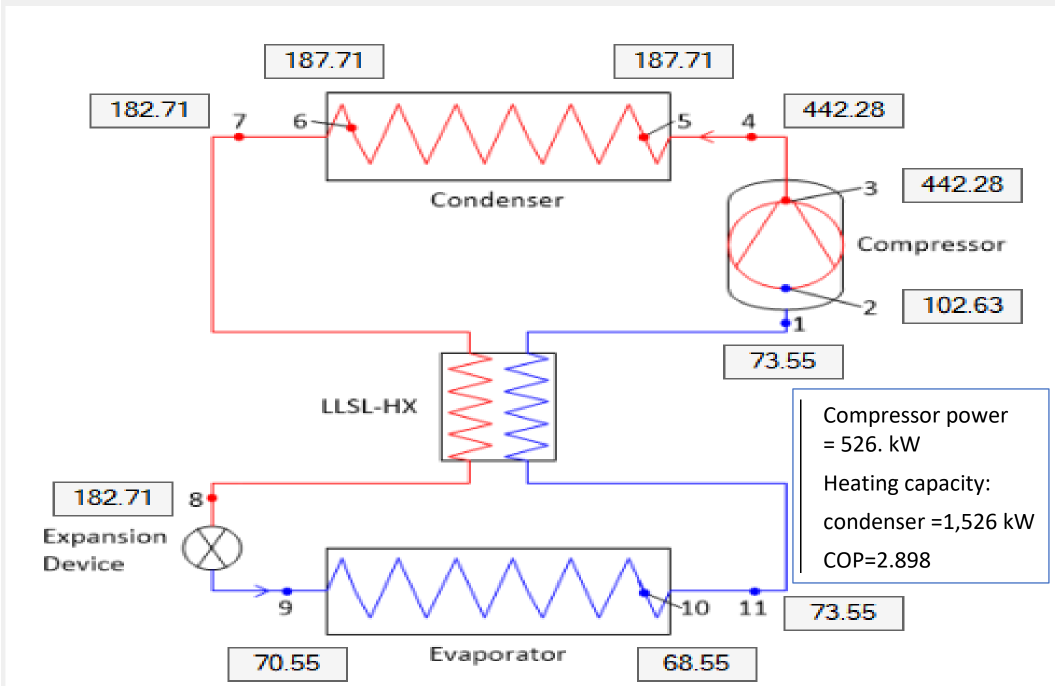


Figure 7: Temperature -Entropy and Pressure-Enthalpy Diagrams with Ammonia as the Working Fluid (Reference 6)

The cycle process flow diagram and process parameters are shown below, where a COP of 2.8 was calculated utilizing ammonia as the working fluid.

Temperature & Pressure Profile of Ammonia Cycle at EIC conditions



	STATE	T (Deg. F)	P (psi)	H (Btu/lb)	V (ft^3/lb)	S Btu/(lbF)	XQ
1	Compr. shell inlet	73.6	125.6	701.6	2.40E+00	1.40252	1
2	Cylinder inlet	102.6	125.6	721.2	2.59E+00	1.43842	1
3	Cylinder outlet	442.3	690.1	898.1	7.63E-01	1.49994	1
4	Condenser inlet	442.3	690.1	898.1	7.63E-01	1.49994	1
5	Cond. sat. vapor	187.7	690.1	691.5	4.02E-01	1.22606	1
6	Cond. sat. liquid	187.7	690.1	335.8	3.26E-02	0.67662	0
7	Condenser outlet	182.7	690.1	328.6	3.22E-02	0.66554	0
8	Exp. device inlet	182.7	690.1	328.6	3.22E-02	0.66554	0
9	Evaporator inlet	70.6	130.1	328.6	6.41E-01	0.69547	0.272
10	Evap. sat. vapor	68.6	125.6	698	2.37E+00	1.39576	1
11	Evaporator outlet	73.6	125.6	701.6	2.40E+00	1.40252	1

Figure 8 Process flow diagram and process parameters for the refrigerant cycle Reference 6

Assuming nominal efficiencies for a realistic refrigeration cycle with reasonable compressor pressures we base the calculations around a nominally conservative COP where commercially available technologies exist.

$$COP_{real} = 2.3$$

So based on a realistic refrigeration cycle this translates to a 58% reduction in fossil fuel energy and a 58 % reduction in associated heat emissions while delivering the same amount of heat. The available amount of heat for the EIC is assumed to be 50 MW.

For the rest of this technical note, the 50 MW EIC heat is assumed to be available at a COP of 2.3.

3 Evaluating Steam Load Demand from the Users

3.1 Current heating usage at BNL

The buildings at BNL are heavily reliant on a high-pressure central steam plant for building heating and hot water. The central plant utilizes fossil fuels including natural gas as its source of combustion energy for the high-pressure boilers. These boilers then typically pipe the steam around the campus to feed individual buildings and generate heating hot water via let-down stations and shell and tube heat exchangers.

There are currently over 100 buildings in the BNL campus that are fed by the steam plant.

#	Name	Ar ft2	#2	Name2	Ar ft22
0097	Facility Operations Center	3,755	0750	High Flux Beam Reactor	117,790
0134	Facilities and Operations	30,593	0801	Isotope Research and Processing	51,135
0179	Staff Services/EENS/Post Office	15,029	0811	Waste Concentration Facility	1,906
0197	NNSD/Graphic Arts/NNDC	52,029	0815	EENS Multiprogram Laboratory	64,228
0355	Users Center/PPM	10,295	0820	ATF / Vacuum Group	29,507
0400	Research Support Center	64,816	8208	ATF Storage Facility	726
0421	Structural Biology	5,980	0830	Environmental Waste Technical Center	28,946
0452	Utilities Maintenance	31,000	0832	NSLS II Accelerator Systems	8,180
0459	Information Technology Division	14,304	0835	Electrical Operations	7,115
0460	Director's Office	17,762	0855	WMF-RCRA	27,474
0461	Gymnasium	13,243	0860	WMF-Operations	12,364
0462	Central Shop - Sheet Metal Shop	21,000	0865	WMF-Reclamation	20,886
0463	Biology	113,546	0870	WMF-Mixed Waste	6,888
0464	DOE-BHSO Group Office	12,777	0901	Radioisotope and Radiotracer C	34,301
0473	Electron Beam Weld	4,894	0901A	Van De Graaff Building	65,611
0477	Research Library	17,807	0902	Magnet Division	135,509
0478	Swimming Pool	19,441	0904	Electricians Work Area	1,769
0479	Heavy Machine Shop	33,926	0905	Magnet Assembly	28,408
0480	Materials Science	40,786	0911	Collider Accelerator Department	100,663
0488	Berkner Hall	52,681	0912	AGS Experimental Halls	181,957
0490	Medical Research Center	222,519	0912A	Mechanical Equipment Building	5,864
0491	Medical Research Reactor	11,653	0913A	Fan House A - Northeast	664
0510	Physics	201,929	0913B	Fan House B - North	654
0515	Information Technology Division	65,836	0913C	Fan House C - Northweat	1,632
0526	Energy Efficiency & Conservation	29,158	0913D	Fan House D - Southwest	662
0535	Instrumentation Division	76,911	0913E	Fan House E - Southwest	671
0555	Chemistry	151,467	0914	Booster Equipment	8,614
0560	High Field MRI Lab	4,033	0919	G-2 Experiment Group	16,463
0599	Fire House	12,148	0919A	AGS Crogenicsrrarget Group	4,876
0600	Chilled Water Facility	12,778	0919B	Works Building	8,234
0603	69 kV Sub-Switchgear Bldg	4,567	0924	• RHIC-Magnet Production/Assembly	19,162
0610	Central Steam Facility	15,946	0928	Siemens MG Power Supply	18,086
0650	Custodial Storage	12,408	0929	RF Power Supply	13,471
0701	BGRR Project Offices	38,641	0930	200 Mev Linac	103,647
0703	Lab/Office Building	84,531	0974	Radioactive Material Storage	22,294
0704	Fan House	9,864	1005S	Collider Center	40,791
0725	National Synchrotron Light Source	155,199		NSLS II.	400,000
0726	NSLS Mech Tech Supply Facility	3,519			
0727	NSLS Mechanical/Magnet Measurement	4,049			
0729	NSLS Source Development Laboratory	8,018			
0735	Center for Functional Nano Materials	95,947			

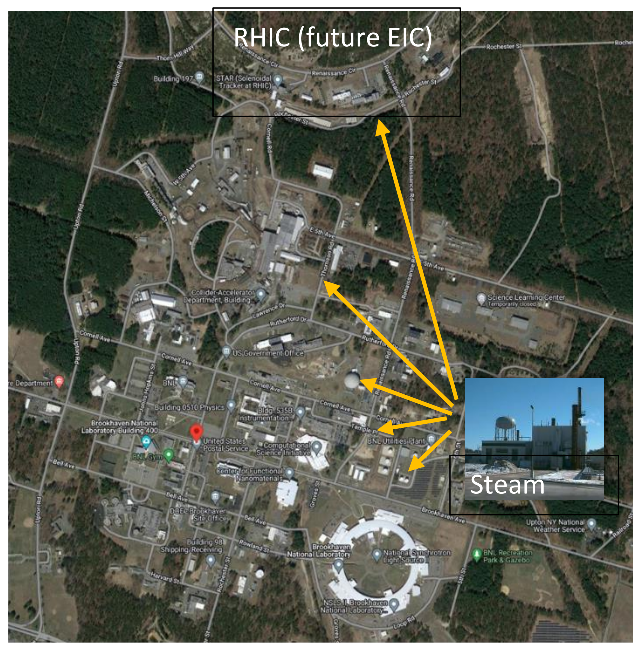


Figure 9 BNL Campus Steam Users and Steam Plant

High-pressure steam at 125 psig is distributed campus-wide and the pressure is let down to around 10 psig, which is utilized to produce hot water in the steam converters (plate and frame heat exchangers). See the schematic below for building 1005s which is a typical representation of the steam distribution network. There are currently approximately 10 miles of steam and condensate distribution piping campus-wide.

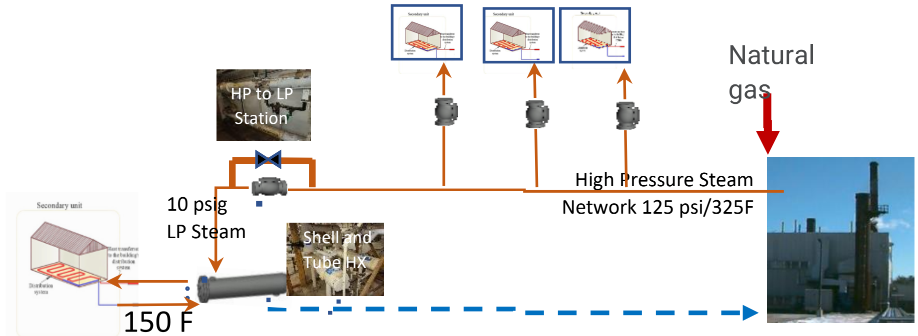


Figure 10 Schematic of the steam distribution to the various buildings

3.2 Integration and Implementation with EIC

The intent of the EIC energy recovery and its use in building heating would be to replace the steam system with the hot water produced by the heat pumps. This could be either via a central hot water production facility or with heat pumps located in each building. Maintaining the 150 Deg. F conditions would imply that the internal piping in the buildings would not have to be replaced and the work could be done during summertime with minimal disruptions.

The figure below shows the operational integration concept with the EIC. When the cooling tower is in operation and there is heat demand, isolation valves would divert the flow to the heat pump in lieu of the cooling tower. Diversion of the flow to the heat pump can be either an on/off sequence or a modulating sequence. However, the system must be designed to have no operational impact on the cooling performed at the EIC.

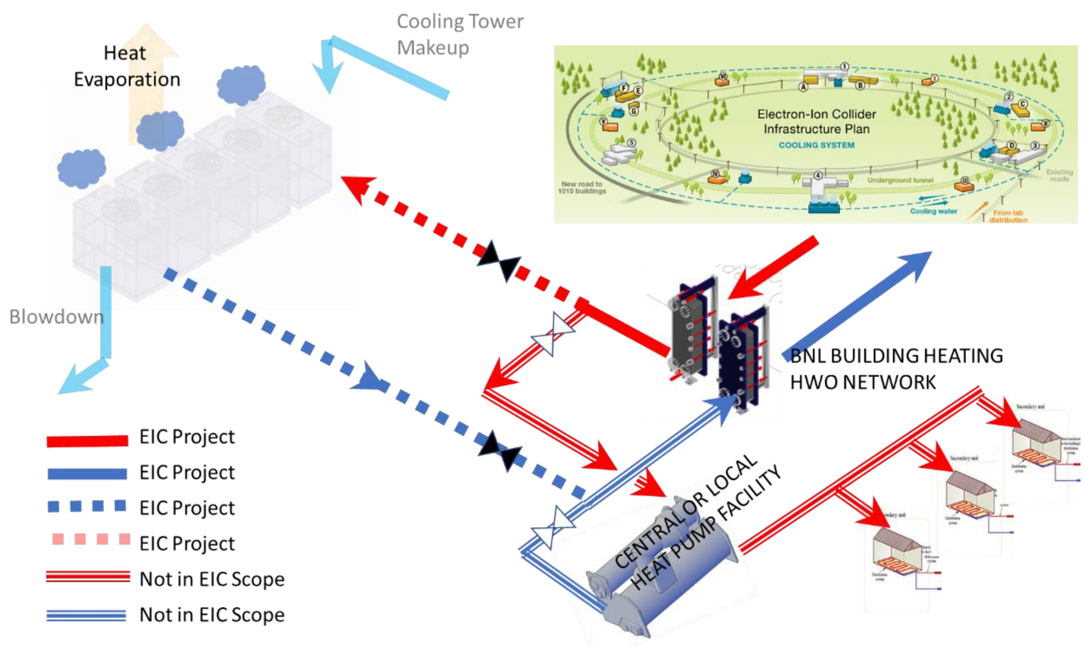
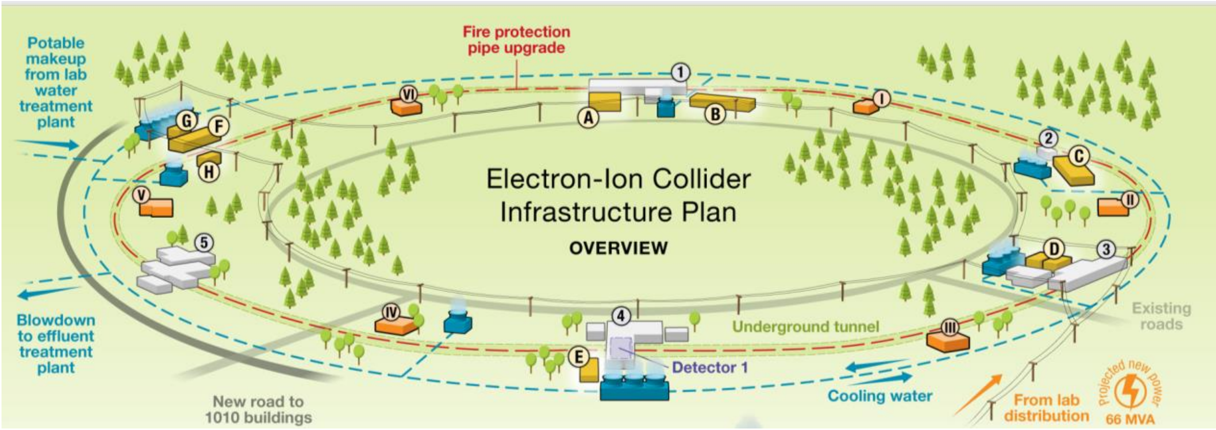


Figure 11 Implementation Concept Operational

Cooling loads for the machine are identified in the following infographic. The majority of the cooling loads occur at IR10, followed by 2 o'clock, 4 o'clock, 6o'clock, and 7 o'clock.



Location	Heat Load	Supply Temperature	Return Temperature
Cooling Tower at 2 o'clock	10 MW	94F	84F
Cooling Tower at 4 o'clock	6 MW	94F	84F
Cooling Tower at 6 o'clock	7 MW	94F	84F
Cooling Tower at 10 o'clock	23 MW	94F	84F

3.3 Analyzing the water Savings Utilizing EIC Waste Heat Recovery

To evaluate the potential for the lab to utilize the EIC waste heat, the total lab steam consumption was analyzed on an annual basis and converted to monthly usage based on degree-day averages obtained from BNL weather data as noted below.

The usage of steam was evaluated based on the FY 2018 demand. Annual steam consumption was estimated to be monthly usage based on averages obtained since 1949.

STEAM	
Fuel	#2 oil, #6 oil, natural gas
FY 2018 production	474,480 klbs
FY 2018 peak demand	166,240 lbs/hr
Steam Pressure	125 psi

Figure 12 Fact Book: Physical Plant Datasheet Site Planning and Infrastructure Mgmt @ BNL

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg	*1099*	*959*	*843*	*530*	*260*	*61*	*7*	*16*	*116*	*374*	*643*	*946*

Figure 13 BNL Degree Days from https://www.bnl.gov/weather/4cast/heatingdegreedays.htm

The monthly average steam consumption is determined as shown below and compared to the average dissipated heat from the EIC machine.

The percentage of utilization of EIC heat was based on comparing the aggregate monthly heating demand to the amount of waste energy dissipated by the EIC. The EIC is not expected to operate in the summer months, which also coincides with the period of heating steam demand. The demand increases in colder months resulting in higher utilization in winter. Based on the utilization analysis below there is sufficient heat available to meet the demands of BNL building heating needs.

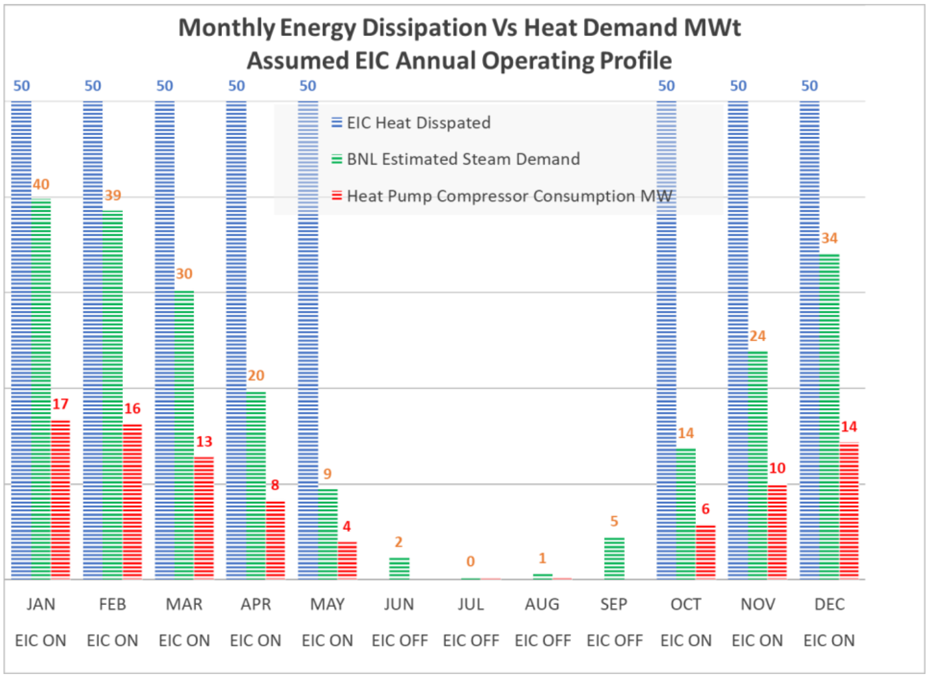


Figure 14 Determining the amount of heat available for Building Heating based on 8-month operation.

3.4 Analyzing Other Savings Utilizing EIC Waste Heat Recovery

Cooling Tower Blowdown and Makeup

Utilization of waste heat for producing building heat has the additional benefit of avoiding cooling tower blowdown and makeup.

The cooling tower utilizes the evaporation of water to dissipate process heat. This evaporated water has to be replaced which is known as the process of makeup.

$$Water\ Evaporation\ Rate = \frac{Heat\ Dissipated}{Latent\ Heat\ of\ Evaporation}$$

The constant evaporation also requires blowdown to avoid precipitation from dissolved solids, which continuously build-up, and is determined by the operating cycles of concentration. The blowdown gets discharged as effluent to the sanitary system.

Hence, the total makeup is given by:

$$Makeup = water\ evaporation + blowdown$$

Based on a 5 cycles of concentration cooling tower, water consumption for the EIC cooling tower can be estimated as follows.

- Cooling Tower Makeup 440 gpm
- Cooling Tower Blowdown 110 gpm

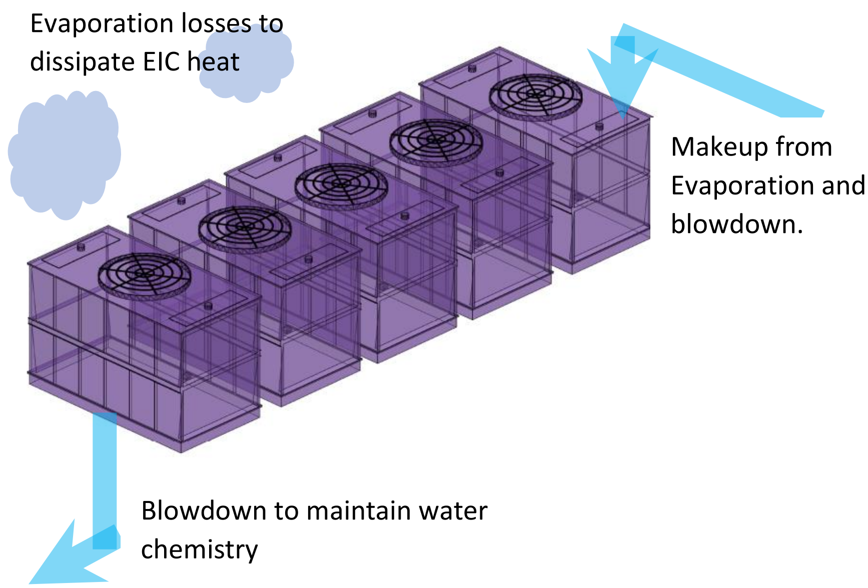


Figure 15 Evaluating Cooling Tower Water Consumption

This results in a savings of 80 million gallons makeup and 20 million gallons blown reduced annually. This assumes all heat is utilized.

Reduction in Carbon Dioxide Emissions

Reducing fossil fuel combustion results in a reduction in CO2 emissions based on the assumption that the boilers would continue to use fossil fuel to generate heating steam in the absence of heat pumps.

Utilizing estimating methods from epa.gov, it is estimated that approximately 0.0004 Tons of CO2/kWh (ref. 7) can be avoided by avoiding fossil fuel consumption. This corresponds to an estimated annual savings of 38,000 tons annually.

Reduction in Fuel Operating Costs

For every MWt (megawatt thermal) energy avoided, there are unit savings in the amount of $57.79 per MWh assuming that all future building heat loads will be converted to electric heat. This results in savings of $5.1 million annually. Note that the all-in electric rate for FY22 was $57.79/MWh, which was up 47% from the FY21 historic low of $30.31/MWh. (Reference 1)

4 Summary Conclusion and Next Steps

The potential benefits of capturing the waste heat generated from the EIC utilizing commercially available temperature lift heat pump technology are summarized below:

- Reduction in Fossil Fuel Consumption 87,300 MWt-hrs Annual
- Reduction in Water Consumption 80 million gallons Annual
- Reduction in Water Effluent Water 20 million gallons Annual
- Savings in Energy Costs $5.1 Million Annual
- Avoided CO2 emissions 38,000 metric tons Annual

4.1 Benefits beyond BNL.

Lastly, the heat not utilized by the lab may have the potential to be exported or to support project expansion needs. As much as 80,000 MWt-hrs of heat may be available to serve the needs of the local community via a local heating network.

5 Next Steps/Recommendation

It is recommended that an engineering study be performed to determine the technical and economic feasibility of the proposed concept.

6 References

1. BNL FY 2023 Annual Site Sustainability Plan
2. EIC Project Preliminary Infrastructure Utility Requirements
3. EIC Project Infrastructure Mechanical Cooling System Design
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