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Authors
O'Neill, Nicholas F
Ma, James Minh
Walther, David Charles
et al.

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A Modified Total Equivalent Warming Impact Analysis: Addressing Direct and Indirect Emissions Due to Corrosion

Nicholas F. O'Neill[1], James Minh Ma[1], David Charles Walther[1], Lance R. Brockway[1], Chao Ding[2*], Jiang Lin[2]

[1] Nelumbo, Inc., 26225 Eden Landing Rd, Hayward, CA 94545
[2] Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA

Abstract

A global rise in HVAC-R utilization requires a deeper understanding of the industry's effect on electricity consumptions and greenhouse gas emissions. The Total Equivalent Warming Impact (TEWI) methodology was designed to analyze emissions from direct release of refrigerant and indirect emissions through electricity consumption of HVAC-R systems to increase the understanding of system design on emissions, and to guide refrigerant replacement. However, the original TEWI calculation neglects the system degradation due to corrosion. This paper studies on the impact of corrosion and highlights how the original TEWI method underrepresents the lifetime emissions due to energy efficiency decrease and refrigerant release. Corrosion impacts direct emissions by increasing refrigerant leakage rates over time and indirect emissions through heat exchanger efficiency degradation and suboptimal refrigerant level. A modified TEWI equation is proposed to capture the dynamic corrosion impacts over the lifetime of HVAC operations. Three scenarios (low corrosivity, conservative and moderate corrosivity) are examined to analyze different corrosion environments. This analysis indicates 6%-27% increase in TEWI emissions based on a typical residential air conditioner (AC), when the impacts of corrosion are included, with the greatest emissions increase from reduced electrical efficiency. The impact of several current and future corrosion protection scenarios on TEWI are also included. Appropriate corrosion mitigation can reduce total lifecycle emissions of systems by 6%~10%. The proposed modified TEWI method is expected to provide a more accurate emission estimation for AC sustainability and policy making.

Keywords: Corrosion; Total Equivalent Warming Impact; Greenhouse Gas Emissions; Energy Efficiency; System Degradation; GWP

1. Introduction: HVAC, Climate Change & Corrosion

Heating, ventilation, air conditioning and refrigeration (HVAC-R) accounts for 17% of the total electricity consumption in buildings, with comfort cooling making up 10% (IEA, 2018) and refrigeration another 7%. The HVAC-R industry growth is accelerating, with the greatest demand occurring in developing nations (see Table 1) with large population centers in the tropic zone which can have up to 5x higher cooling needs as measured by cooling degree days (CDD)(Velders et al., 2010). Demand in the tropics is further expanding through needing to support an increasing share of the global population, from 40% to 50% by 2050, as well as enhanced living standards within the region. However, growth is not isolated to the tropics with global migrations and shifting climate patterns. Based on a recent IEA report, the projected space cooling demand growth mainly comes from emerging economies, among which India, China and Indonesia alone contributing 50%. By 2050, it is predicted approximately a1500% increase in India, a 200% increase in China and a 1300% increase in Indonesia (IEA, 2018). Developed nations which historically had low comfort cooling system adoption rates are expected to grow as well. For example, the cooling demand in the US will increase by 40% in 2050. Europe, with a 20% adoption rate of air conditioning (Sebi, 2019), is expected to more than double the number of installed units by 2050 (Noack and Hassan, 2019). So while not expected to be the major contributor to global AC growth, growth in historically stagnant developed-markets is expected to accelerate alongside growth in emerging markets in response to more extreme climate conditions.

The scale and growth rate of the industry has led to concerns about the impact of HVAC-R on climate change, from both the electrical consumption as well as the release of refrigerants with global warming potentials up to 4000x more potent than CO_2 into the environment (CARB, 2019)

Table 1: Room AC Sales by Region, 2011-107 (millions of units) (ChinaIOL, 2018; JRAIA, 2018)

	2012	2013	2014	2015	2016	2017	Average Annual Growth
China	99.8	128.5	126.9	107.4	117.5	140	8%
Asia - Excluding China	20.3	21.4	21.7	21.8	23.3	24.7	4%
Europe	6.3	6.1	4.9	4.7	5.4	5.8	-1%
North America	7.5	7.9	8.2	8.1	8	8.1	2%
South America	6.6	7.1	7.4	6.6	5.8	6.1	-1%
Middle East	3.7	4.7	4.8	4.7	4.6	4.4	4%
Africa	2.2	2.3	2.3	2.3	2.4	2.3	1%
Oceania	0.8	0.8	0.9	0.9	0.9	1.1	7%

Safety and environmental analyses in the HVAC-R industry have, on multiple occasions, driven extensive international cooperation to mitigate global technology issues. In the 1920's, highly toxic refrigerants, including methyl chloride and sulfur dioxide, were replaced with chlorofluorocarbons (CFC's) - synthesized substances tailored for use in HVAC-R that were both more efficient and less harmful to human health. CFC's were used well into the 1980's until consensus on their damage to the Ozone Layer led to the Montreal Protocol (Montreal Protocol,1987), an international collaboration to retire CFC's quickly with an additional phase out of hydrochloroflurocarbons (HCFC's) and hydrofluorocarbons (HFC's). In 2016, the adoption of the Kigali Amendment to the Montreal Protocol (Heath, 2017) added regulations of global warming potential (GWP) of refrigerants used in HVAC-R. Transition to low GWP refrigerants is estimated to avoid a 0.5°C temperature rise and energy efficiency improvements are expected to double the benefit (Xu et al., 2013). Addressing both items are critical to achieving meaningful GWP reduction targets such as those outlined by Paris Climate Agreement of <2.0 °C rise by 2030.

The Total Equivalent Warming Impact (TEWI) methodology (Fischer,1993) analyzes the global warming impact of HVAC-R systems by considering both direct (refrigerant leakage) and indirect (electrical consumption) emissions as a result of system operation. Originally developed as a tool to quantifiably compare emissions as a cost-benefit tool when considering lower GWP refrigerants with lower thermodynamic efficiencies, TEWI analyses have suggested that up to 80% of CO_2 equivalent emissions come from indirect sources, leading to larger scrutiny and demand in developing nations on unit efficiency (Khanna et al., 2019; Karali et al., 2020). TEWI analyses were designed to compare lower GWP refrigerant alternatives by incorporating system performance estimates, not to accurately estimate equivalent emissions for the operational lifetime of a system (UNEP, 2019).

In an operating lifetime, direct and indirect emissions rates change and degrade in an interrelated fashion. For example, loss of refrigerant affects system cooling efficacy which increases runtime and energy efficiency, further increasing electricity consumption and potentially leading to system failure. Corrosion leads to performance degradation and small-scale refrigerant leakages, accounting for an estimated 40% of HVAC-R equipment failures (Bhatia, 2019). However, this impact is not considered in the current TEWI calculation. To fill this gap, this study expands the TEWI methodology to include system degradation to evaluate the impact of corrosion on global CO_2 equivalent emissions (CO_2e) for the HVAC-R industry to inform future efficiency policy goals.

2. Expanded TEWI

Although TEWI is designed to address the impact to the environment over a defined time period, many studies neglect system degradation (Islam et al., 2017; Mylona et al., 2017; Antunes and Filho,2016), which leads to underestimates of both direct and indirect emissions. While degradation in system performance results from several factors, such as dirt and debris fouling (Ahn et al., 2003) of the heat exchanger and/or mechanical wear of the components, this study is focused only on the impacts of corrosion.

Another compounding factor is that both direct and indirect emissions can be affected simultaneously. For example, there is a well-studied link between the total mass of refrigerant (refrigerant charge) in an HVAC-R system and its optimal electrical efficiency. Excessive over or undercharging leads to decreased performance (Kim and Braun, 2012; Hu et al., 2017; Mehrabi and Yuill, 2017; Grace et al.,2005).

We propose a Modified TEWI – outlined in Figure 1 – to evaluate the impact and scale of the corrosion degradation on HVAC-R global warming equivalent emissions. Our modified TEWI structure independently evaluates direct emissions into venting and leakage of refrigerant, and indirect emissions are broken into rated electrical efficiency and electrical efficiency degradation. The impact of corrosion on each of these categories is considered in the following sections.

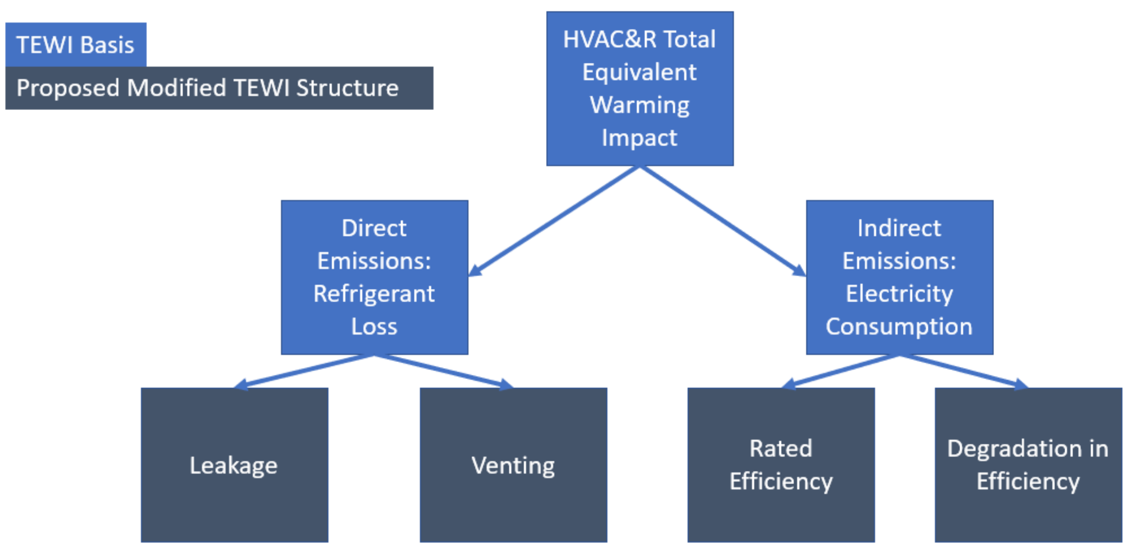

Figure 1: Modified TEWI Approach – Graphical Representation.
The overall TEWI approach was broken down another layer to account for the impacts of corrosive degradation. This flow chart represents the logical extensions of the emissions categories that are explored in the paper

2.1. Direct Emissions

Direct emissions from refrigerant leakage and venting during maintenance are difficult to quantify. Further attributing these direct emissions to corrosion-specific impacts is even further complicated. As such, the potential impacts of corrosion on direct emissions through leakage or venting/maintenance are discussed but no changes to the direct emissions portion of the TEWI methodology are recommended.

2.1.1 Refrigerant Leakage

Corrosion induced leakage on refrigerant carrying coils and piping causes loss of refrigerant to the atmosphere. The US EPA requires owners of systems with 50lb or more of refrigerant charge to report leaks that exceed the "trigger rate" for leakage set by under Section 608 of the Clean Air Act (EPA, 1993), depending on the size and industry of the system in question. However, there are no reporting requirements for systems under 50lb of charge at the federal level and leakage rates up to 30% for certain unit types do not require reporting under the new guidelines.

The EPA estimated that the updated requirements would prevent 7.3 million metric tons of CO_2 equivalent emissions per year, with over half of that coming from the comfort cooling. The EPA reporting charge size requirement neglects almost all the 102.8 million household (EIA, 2015) and small commercial units, containing an estimated 750 million pounds of refrigerant (based on average charge size of units) and a direct emission-only impact of up to 0.65 gigatons CO_2e. Similarly, a survey of multiple European countries through the RealSkillsEurope program shows that, for many refrigeration systems, the leakage rate is up to 10% annually (Koronaki et al., 2012), whereas an extensive study by the UK Department of Energy & Climate Change found that the average annual leakage rate for operating systems is 3.5% for domestic units and 3.8% for non-domestic units (DOE, 2014). With the difference in regulations and comprehensive studies, it appears there is a range of under 5% to over 30% in yearly leakage depending on type of unit and location. With corrosion being a primary cause of leakage in HVAC-R units of all sizes (Durrani et al.,2019; Bastidas et al.,2006; Peltola and Lindgren, 2015), it is difficult to attribute the full direct emission effects from corrosion.

Under a California Public Records Act (PRA) request on leakage repair reports from 2018, the California Air Resources Board (ARB) provided data to the authors for 2018 showing over 2.4 million pounds of refrigerant was added to over 13,000 systems that were found to be leaking (CARB, 2018). This accounted for over 18% of the total charge capacity of the systems with reported leaks in just that year, and only includes systems with a charge volume of over 50 lbs, which fits within the bounds found in similar studies.

2.1.2 Venting

Small quantities of refrigerant are vented during installation, maintenance or decommissioning events due to the need to purge air and form connections to pressurized equipment. In the United States, purposefully venting refrigerants is illegal under the Clean Air Act (EPA, 1993), although *de minimis* quantities are allowed if making a good faith effort in recovery. These allowable vented quantities comply with EPA guidelines up to 10% of total system refrigerant charge units with more than 50 pounds of charge, making collection of venting data difficult.

The corrosion effect on venting can be estimated through the increased frequency with which installation, maintenance and decommissioning events occur. HVAC-R maintenance from corrosion is a non-trivial problem within the United States, especially in more corrosive coastal or industrial environments. The US Department of Defense has estimated that 3% of their yearly maintenance budget goes to HVAC corrosion, with general corrosion accounting for 15% (Chang, 2019; Beitelman and Drozdz, 2015).

2.2 Indirect Emissions

2.2.1 Degradation in Efficiency

Current TEWI analyses focus on as-rated electrical efficiency to determine the impact on indirect emissions, leadingto positive increases in air conditioners' minimum energy performance standards (MEPS) around the world (DOE, 1989; GB 21455, 2019; EU Commission Regulation, 2012; Air Conditioner Evaluation Standard Subcommittee,2006). Maintenance of degraded electrical efficiency is an industry focus, but the effect on global warming impact has not been well analyzed (Electrofin. 2020). Unit degradation reduces electrical efficiency warranting a modification to the TEWI parameters.

Corrosion has a multi-faceted impact on electrical efficiency of HVAC-R units, affecting system performance through charge loss and degraded air-side heat transfer efficiency. Loss of refrigerant from corroded areas decreases cooling efficiency in a mechanism known as "under-charging", where there is not enough refrigerant within the system to adequately transfer heat for the given demand (Hunt et al., 2010). Many units are designed with buffer refrigerant reservoirs which can help deal with variable heat loads – such as an accumulator after the evaporator and/or a receiver after a condenser - or are over-charged to maintain system efficiency through small charge losses without significant efficiency impact from overcharging (Kim and Braun, 2012). However, there is a sharp decline in system performance when the charge level is depleted beyond a threshold (Cowan, 2010). Leakage costs have been parametrically analyzed to include both leakage replacement and additional energy costs (Carbon Trust, 2019) to counteract the efficiency decrease, with the energy related costs surpassing the leakage replacement quickly.

The buildup of corrosion products and coil damage reduces the heat transfer efficiency and increases electrical consumption. An example of corrosion on a heat exchanger coil for a residential air conditioner can be seen in Figure 2.

Figure 2: Air conditioning unit showing signs of corrosion (left). The expanded picture of the coil shows loss of fins and accumulation of corrosion products that affect system efficiency (right).

Furthermore, corrosion products can obstruct heat exchanger airflow, affecting fan power and reducing overall heat exchanger effectiveness. In highly corrosive environments, bare HVAC coils can lose up to 50% of operating capacity within a year from corrosion (Bhatia, 2019). Previous laboratory studies (Zhao et al., 2012) have used ASTM standard tests (B117) to analyze the air-side heat transfer degradation in fins as a proxy for corrosion, showing significant performance degradation occurs under 50 hours of exposure in the salt-spray test. These findings align well with the observation of significant degradation in 2 years of multiple constructions of HVAC coils – both bare and coated – in corrosion exposure testing by the US Navy (Roe et al., 1979).

2.2.2 Rated Efficiency

HVAC-R system performance is driven in part by the ability to reject heat to the atmosphere through the condenser. Corrosion resistant coatings are used to increase condenser life in corrosive environments. Most coatings use polymers that decrease heat transfer efficiencies from the bare metal coil due to the thickness of application and low thermal conductivity of the coating. Examples of corrosion protection schemes include phenol, polyurethane, silane or other polymer layers on top of the metal coil and can be applied through dip, spray, or electrodeposition methods. Coatings can reduce heat transfer efficiency of the coil by 2-6% (Electrofin,2020) and increase pressure drop across the coil by upwards of 20% and thus input fan power. This problem is acutely important in high efficiency systems using microchannel heat exchangers where airflow occurs through small areas. These impacts lead to a reduction in unit efficiency from the rated value and an increase in global warming impact. Though the performance tradeoff for system survivability versus efficiency impact is well understood within the HVAC-R industry (Turpin, 2002), the global warming impact is underestimated or neglected in the broader policy-oriented community.

This tradeoff poses an interesting environmental benefit problem, analogous to those addressed by the original basis of the TEWI methodology. Although a coating to protect against corrosion decreases initial electrical efficiency, it ultimately extends system lifetime and prevents performance degradation better than a bare metal condenser coil. The Civil Engineering Lab of the US Navy studied the efficiency degradation of HVAC units in temperate marine environments and demonstrated this effect in 1979 (Roe et al., 1979). An estimate of the total global coil coatings for corrosion protection market is $6 Billion (MarketsAndMarkets, 2014), with an anticipated increase in growth rate due to corrosive region HVAC-R growth. This large market suggests that a large portion of HVAC-R units have electrical efficiency reduced by up to 4% lower compared to rated values. Units with corrosion protection applied carry the performance and electrical efficiency label of the non-coated stock unit due to the expense and challenge of testing all system and coating configurations, underestimating the equivalent emissions of the market

3. Modified TEWI Calculation

The original TEWI calculation methodology follows Equation 1 (Maykot et al., 2004) below:

$$TEWI = GWP * \left(m * L_{annual} * n + m * (1 - \alpha)\right) + E_{annual} * \beta * n \qquad (1)$$

where:
GWP = Global Warming Potential of Refrigerant
m = refrigerant charge (g)
L_{annual} = annual leakage rate (%)
n = number of years of operation
α = recovery/recycling factor (0 to 1)
E_{annual} = average annual energy consumption (kWh)
β = Indirect Emission Factor in gCO_2/kWh electricity consumed. Varies by location.

A proposed modification to the indirect emission portion of the TEWI methodology to reflect the year-over-year degradation in system performance described earlier is shown in Equation 2:

$$TEWI = GWP * \left(m * L_{annual} * n + m * (1 - \alpha)\right) + \sum_{0}^{n} [\, \gamma_{total}(n) * E_{annual,0}] * \beta \quad (2)$$

where $E_{annual,0}$ is the initial annual energy consumption (kWh); The new term, $\gamma_{total}(n)$, is the corrosion-induced energy efficiency degradation function that addresses charge reduction, coil heat transfer effectiveness reduction from corrosion and from corrosion protection strategies, which changes yearly.

This function is time-averaged, and as a result requires the summation term to track indirect emissions. This efficiency degradation function is modeled as shown below:

$$\gamma_{total}(n) = \frac{1}{1-\delta_{coat}} * \frac{1}{1-\delta_{corr}(n)} * \frac{1}{1-\delta_{charge}(n, L_{annual})} \qquad (3)$$

where:
δ_{coat} = efficiency penalty from corrosion protection coatings
δ_{corr} = efficiency penalty from corrosion, which is a function of time and input degradation rate
δ_{charge} = efficiency penalty from loss of charge, which is based on time and annual leakage rate

The calculation regarding the direct emission portion of the TEWI analysis remains unchanged as noted in section 2.1.

The δ_{coat} term is determined by the heat exchange capacity reduction to initial baseline performance due to corrosion protection coatings. Some coatings can reduce heat transfer by less than 1% (Coilmenplus, 2019; Geoclima 2019), but for full environmental durability an additional UV-resistant coating layer is needed, which can reduce heat transfer up to 4% of baseline analysis (Alcoil, 2015; Modine,2019). The δ_{corr} and δ_{charge} terms correspond to the estimated heat transfer efficiency reduction as a result of condenser coil corrosion and refrigerant charge loss from a system due to leakages.

3.1. Investigation of Corrosion Heat Transfer Degradation

Multiple studies have analyzed heat transfer performance degradation from corrosion (Zhao et al., 2012; Su et al., 2015), showing that corrosion significantly impacts heat transfer efficiency even after a short amount of time. In this study, a simplified model using the NIST CYCLE_D-HX (Brown et al., 2019) software program was used to model the degradation in cycle coefficient-of-performance (COP) as a proxy for electrical efficiency, with the simplified cycle diagram shown in Figure 3. More information on the Cycle_D-HX model is shown in Appendix B.

Air-side heat transfer is modeled through the simplified equation shown below:

$$Q = UA\Delta T \tag{4}$$

where U is the overall heat transfer coefficient and A is the effective surface area, generally considered as UA for heat transfer studies. In the case of corrosion, UA is appropriately taken together as corrosion products can increase thermal resistance through an overall heat transfer coefficient, but also change the effective surface area. Studies have shown that condenser coils can lose 50% of their heat transfer capability as soon as a year (Bhatia, 2019) or ten (Ener.co, 2019), but the simplified model in this study used a 50% decrease in UA over 15 years with an estimated decrease in UA of 3.33% each year due to corrosion as a baseline. These results fall within corrosive environment limits (Beitelman and Drozdz, 2015), keeping well within the Naval studied boundaries for temperate marine locations (Roe et al., 1979). The CYCLE_D-HX model with the example rooftop condenser conditions shown in Figure 3 was then used to simulate the effect of the decrease in UA on the overall cooling-mode coefficient of performance (COP) of the system. COP is a direct measure of system energy efficiency. This relationship is shown in Figure 4.

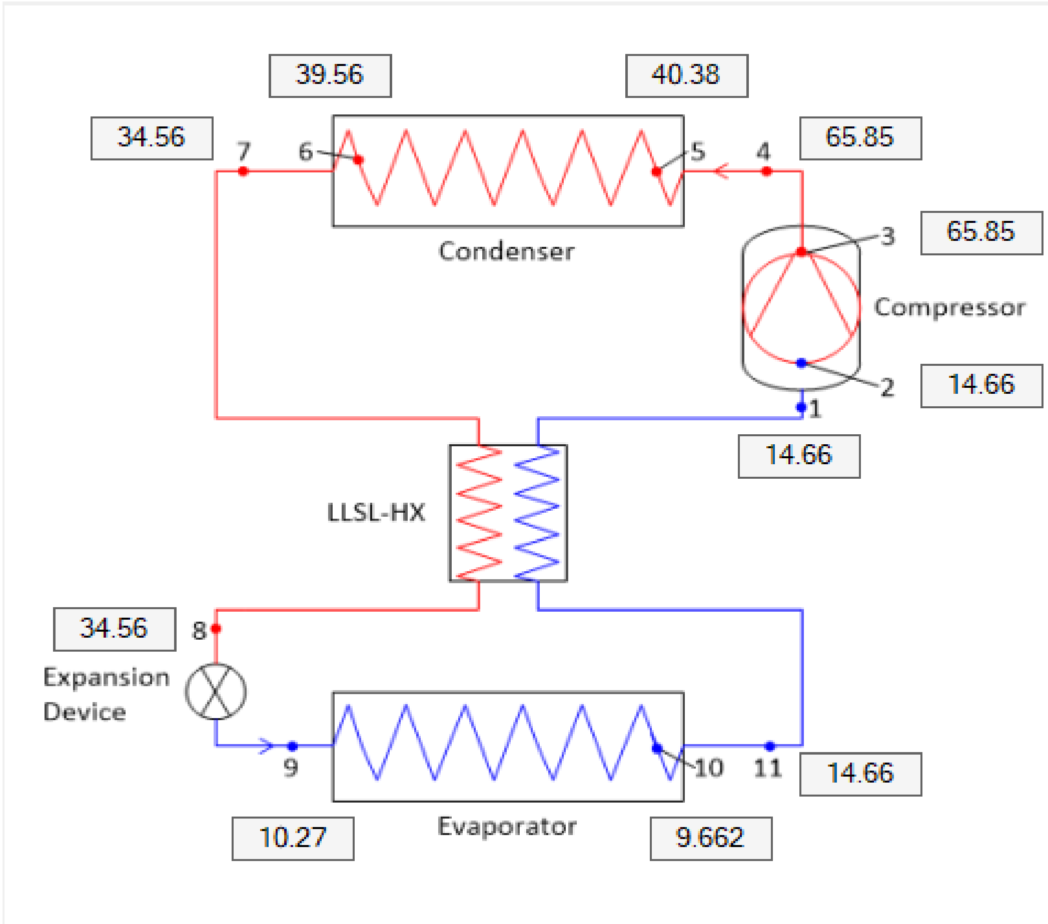

Figure 3: NIST-CYCLE_D-HX Simplified Single Stage HVAC

The NIST-Cycle_D-HX Software was used to examine a simplified rooftop condenser degradation on system efficiency through imposed UA loss over time. The results provided a relationship between % COP decrease tied to % UA loss which formed the basis for the δ_{corr} *term for the modified TEWI equation.*

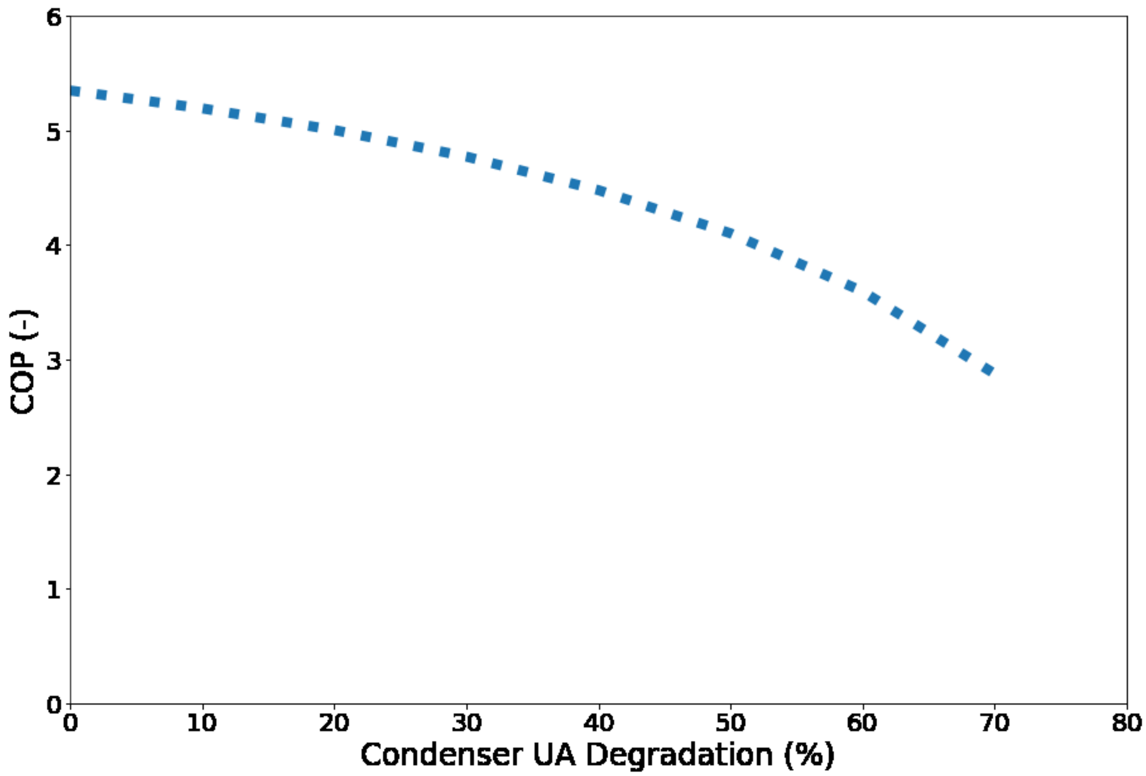

Figure 4: Unit Efficiency Degradation from Assumed Corrosion

The curve was derived through imposing a UA degradation on a rooftop condenser simplified mimic created in NIST Cycle_D-HX software, with the model shown in Fig. 3. The relationship here shows COP, derived from kW output/kW input,, loss as a function of UA % loss, itself derived from COP vs. UA relationship that is modeled in the system. Percent changes were determined as more generalizable.

The COP degradation was evaluated over the 15-year lifecycle to analyze full system performance degradation, with the percent reduction becoming the δ_{corr} parameter in the degradation study. The resulting COP change per year is shown in Figure 5 with the relative percent change shown in Figure 10*: Heat Exchanger Efficiency Reduction over Lifetime*

This relationship was determined for bare (uncoated) condenser coils. A conservative estimate for the corrosion heat transfer reduction of coated coils was taken to be that the coils would undergo the same corrosion profile, but delayed by 10 years in the analysis, which is longer than a typical unit warranty (Modine, 2020). This comparison was calculated using the correlations described above for γ_{total} in Equation 3, with the resulting δ_{corr} values calculated in Appendix A for each case.

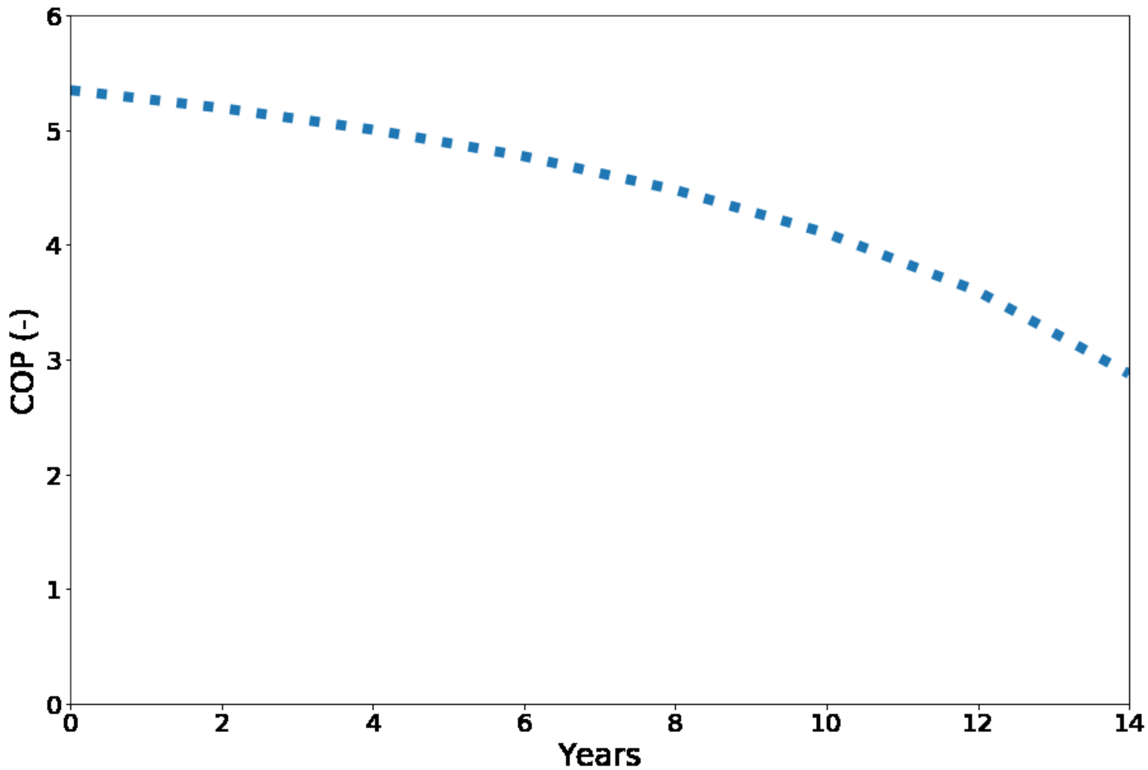

Figure 5: COP Change Over Lifetime

3.2 Investigation of Charge Reduction on Heat Transfer

To model δ_{charge}, a representative residential HVAC-R unit data from Kim and Braun (2012) that modeled the impact of refrigerant charge loss on relative COP was used to as a measure of COP loss similar to the δ_{corr} data. This relationship is shown Figure 6. The results of the COP efficiency change based on the charge reduction profile, assuming a 1% leakage rate per year is shown in Appendix A for each case. The Kim *et al.* data used for the analysis was a conservative estimate compared with other studies (Islam et al., 2017), but showed a similar profile of accelerating COP loss as the system becomes more undercharged. A delayed effect in δ_{charge} for coated cases was used like the delayed onset used for δ_{corr}.

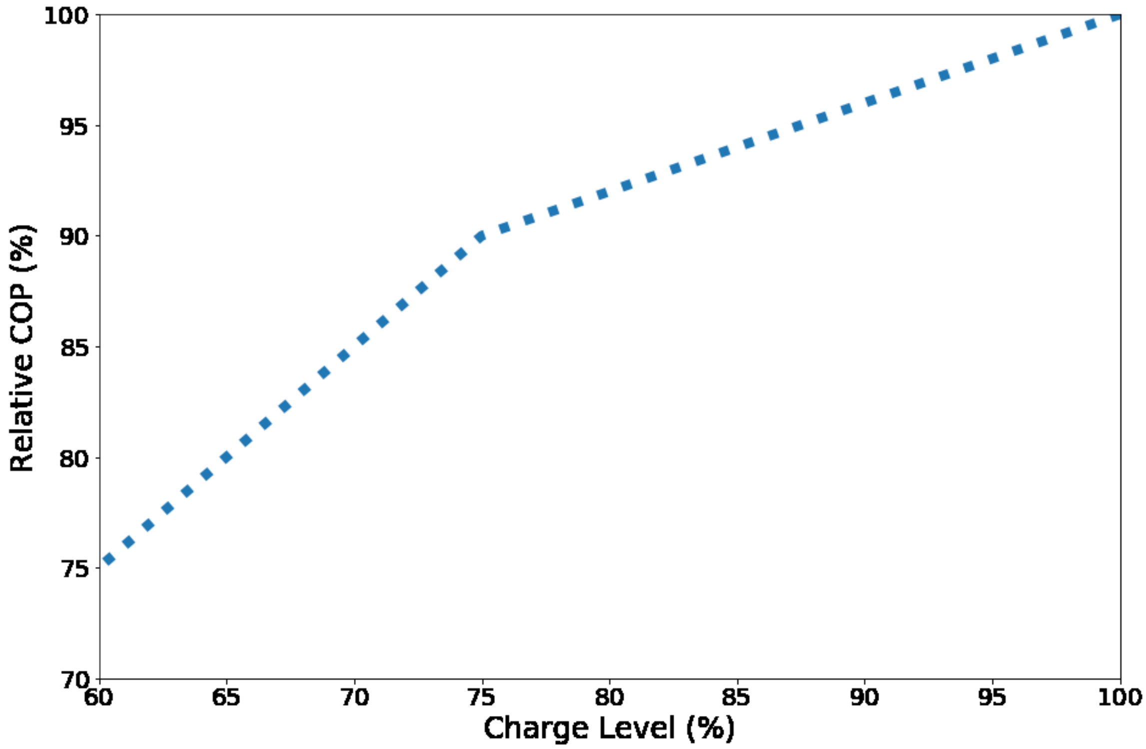

Figure 6: Relative Change in COP with Charge Loss (Islam et al., 2017)

3.3 Relative TEWI Comparison with Degradation Terms

Vohra and Baxter (2004) conducted multiple TEWI analyses, and their assumed 'Atlanta' located, R410A roof-top AC unit analysis is used as the indirect emission basis for the comparative study. Three comparative cases were studied (further details in Appendix A):

1) Conservative Case: Derived throughout the paper, this case models a 21% UA degradation over 15 years
2) Low Corrosivity Case: A 20% UA degradation , but weighted towards last four years.
3) Moderate Corrosivity case: A 50% UA degradation in ten years.

The cases were analyzed using estimated UA degradations and leakages for coils with corrosion resistant coatings as well. The results of the calculations using the modified TEWI equation are shown in Table 2, with the resulting bare coil trends seen in Figure 7.

Table 2: Indirect Emission Increase over Original TEWI

	Low Corrosivity	Conservative Corrosivity	Moderate Corrosivity

Modified Bare Coil	5%	12%	28%
Modified Coated Coil	6%	7%	10%

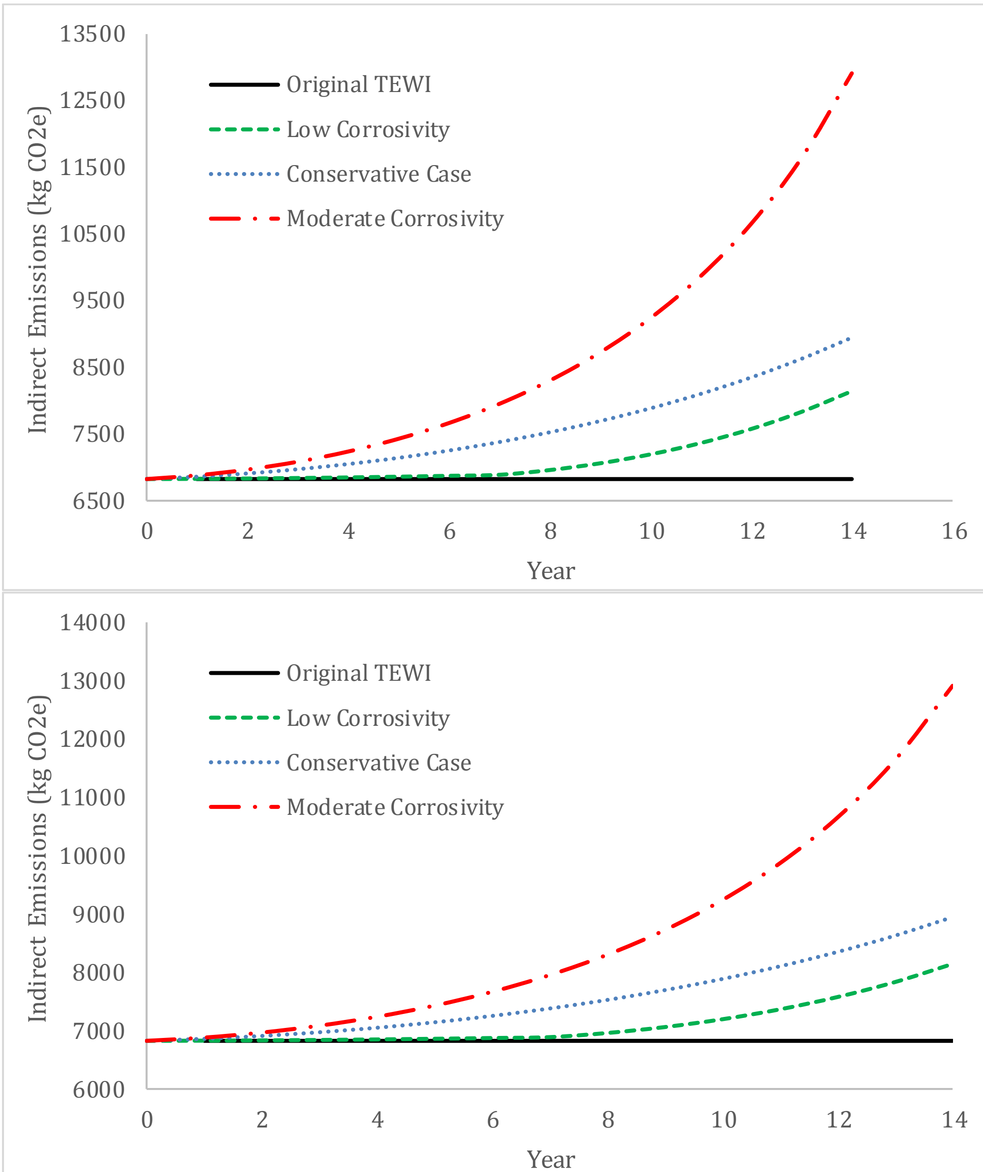

Figure 7: Modified Coated TEWI Emissions. Original (Vohra A and Baxter, 2004); Modified Conservative Case – 15yr indirect emissions; Modified Low corrosivity Case – 20% degradation, weighted to later years; Modified Aggressive Case – 50% degradation, 10yr indirect emissions.

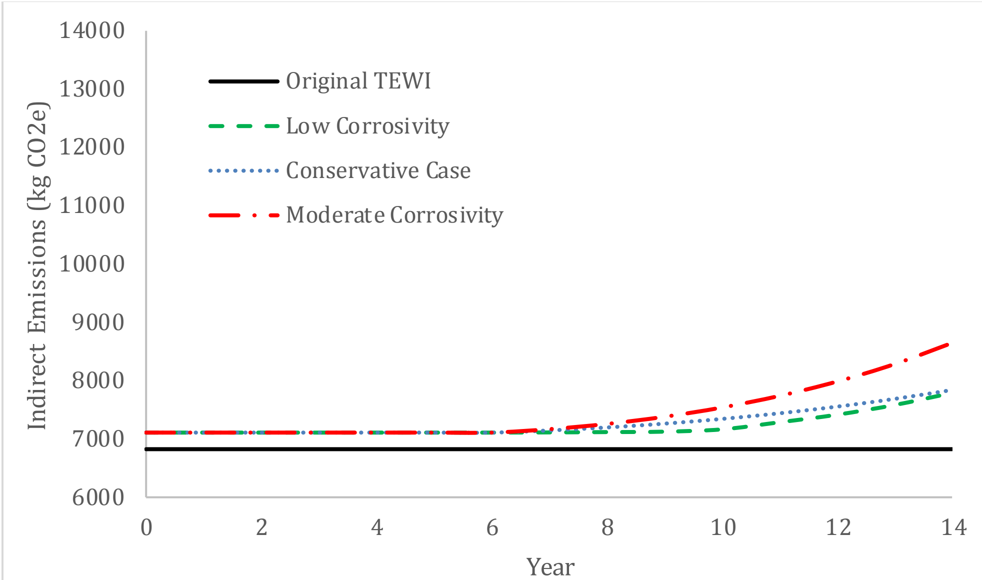

Figure 8: Modified TEWI Comparison using Coated Coil Systems. Analysis done similar to Figure 7. Note the initial increase in indirect emissions due to efficiency loss from coating.

The tabular data supporting the analyses in Figure 7 can be found in Appendix A.

4. Discussion

Figure 7 lays bare in the limitation of standard TEWI calculations for indirect emissions when considering electrical efficiency over unit lifetime. This assumption can hold for short term considerations in low or conservative corrosivity cases, but the compounding effects of corrosion accelerate system degradation in later years of system lifetime. In the 15-year operational lifetime considered, the low corrosivity case underestimates TEWI by 8%, the conservative case by 12%, and the moderate case by 28% in total, but when just the later years of operational lifetime are considered these numbers are significantly higher. This suggests that the degradation of system performance due to corrosion or other factors has a large effect on equivalent emissions of HVAC-R units that is currently not counted within analysis efforts. Decision makers relying on TEWI or similar analyses to evaluate policy alternatives may be underestimating indirect emissions by up to 27% depending upon location. Given where HVAC-R growth is occurring as shown in **Error! Reference source not found.**, this underestimation may be even larger due to the corrosivity of near-equatorial regions.

The unit efficiency penalties from corrosion protection are analyzed in Figure 8, showing a similar – yet smaller – trend as Figure 7. When comparing the cases, the initial penalty due to increased heat transfer resistance is evident. In low and conservative cases, the payback from indirect emission benefit of using the corrosion protection scheme appears only in the last years of the TEWI calculation with the rapid degradation of the uncoated coil compensating for the initial penalty. The low corrosivity case also displays the unintended consequence of producing a higher indirect emission when coated compared with not coated due to the initial coating heat transfer penalty.

This analysis is based on simplified models of the vapor-compression HVAC-R cycle to obtain estimates of system degradation due to corrosion and charge loss. Many HVAC-R systems are complex networks of components, making a degradation style analysis, as was done here, more difficult to achieve and unlikely to lead to generalizations. System operating efficiency is also an interrelated relationship of parts that are susceptible to normal mechanical wear through operation on top of corrosion damage. As a result, it is difficult to identify deterministic sets of data, leading to the simplified modeling approach used to estimate the degradation effects. While other studies have confirmed that units across the HVAC-R spectrum do not operate at their electrical rating efficiency in field conditions (Duggal and Singh, 2016), a further analysis of network scale degradation – given the proper data – would provide insight into the assumptions taken herein. .

Another area that is difficult to quantify is the impact of over-charging refrigerant on HVAC-R systems where not enough charge is added to decrease initial performance of the system. As previous studies have shown, over-charging by up to 20% on most systems will not impact COP, allowing a significant portion of refrigerant to leak without a noticeable impact to electrical efficiency. However, over-charging increases the original TEWI due to the direct emissions associated with loss from the higher initial charge. With guidelines suggesting that reporting of commercial system leaks need only occur above 10-15% or more in a year, many systems are over-charged in order to maintain system efficiency while still abiding by local government regulations.

5. Conclusion

With the rapid urbanization and improved quality life environment, the world is experiencing a dramatic increase in cooling demands and greenhouse gases emissions. The TEWI method is a powerful tool to quantify the global warming impact of HVAC-R systems by considering both direct and indirect emissions of system operation. Although HVAC-R industry has long understood the impact of coil corrosion and refrigerant charge on system performance, these trends have not been adequately accounted for in global warming impact analyses. The traditional TEWI neglect system degradation due to corrosion, which is an inevitable phenomenon during the lifetime of a HVAC system. With the importance of TEWI type analyses in policy making and trade-off studies, a modified TEWI is proposed to incorporate corrosion related degradation into a simplified form.

Three corrosion environment scenarios (low corrosivity, conservative and moderate corrosivity) are discussed in this paper. The analysis shows that corrosion can lead to a 6%~27% TEWI indirect emission increase for a typical residential AC, compared to the original static TEWI calculation method. It is suggested that corrosion mitigation without a decrease in rated electrical performance could reduce total lifecycle emissions of systems by 6%~10%.. The results can provide useful suggestions for HVAC industry to both re-examine and reduce electrical consumption and total emissions in order to meet the internationally proposed climate change initiatives.

6. APPENDIX A

Constants used from Baxter et al:

Initial Charge	5.7	kg
Annual Energy Use	10500	kWh
Beta	0.65	kgCO2/kWh
Lifetime	15	years
Leakage Rate	1%	
Recovery Rate	85%	

Baseline Case (Vohra and Baxte, 2004) with Conservative Corrosion Modifications

Year	Indirect Emissions - Original TEWI Calculation (kgCO2e)	δ_coat uncoated	δ_corr uncoated	δ_charge uncoated	γ Uncoated	Indirect Emissions CO2e Non-Coated (kgCO2e)	δ_coat Corrosion Protection	δ_corr coated	δ_charge coated	γ Coated	Indirect Emissions CO2e - Coated (kgCO2e)
0	6825	0%	0%	0%	100%	6825	4%	0%	0%	104%	7109
1	6825	0%	0%	0%	101%	6860	4%	0%	0%	104%	7109
2	6825	0%	1%	0%	101%	6909	4%	0%	0%	104%	7109
3	6825	0%	2%	0%	102%	6972	4%	0%	0%	104%	7109
4	6825	0%	3%	0%	103%	7050	4%	0%	0%	104%	7109
5	6825	0%	4%	1%	105%	7143	4%	0%	0%	104%	7109

6	6825	0%	5%	1%	106%	7252	4%	0%	0%	104%	7109
7	6825	0%	7%	1%	108%	7380	4%	0%	0%	105%	7146
8	6825	0%	8%	1%	110%	7526	4%	1%	0%	105%	7197
9	6825	0%	10%	1%	113%	7694	4%	2%	0%	106%	7263
10	6825	0%	12%	2%	116%	7885	4%	3%	0%	108%	7343
11	6825	0%	14%	2%	119%	8102	4%	4%	1%	109%	7440
12	6825	0%	16%	2%	122%	8349	4%	5%	1%	111%	7555
13	6825	0%	19%	3%	126%	8628	4%	7%	1%	113%	7687
14	6825	0%	21%	3%	131%	8946	4%	8%	1%	115%	7840
	96	MTCO2e				107	MTCO2e				102 MTCO2e

Moderate Case:

Year	Indirect Emissions - Original TEWI Calculation (kgCO2e)	δ_coat uncoated	δ_corr uncoated	δ_charge uncoated	γ Uncoated	Indirect Emissions CO2e Non-Coated (kgCO2e)	δ_coat Corrosion Protection	δ_corr coated	δ_charge coated	γ Coated	Indirect Emissions CO2e - Coated (kgCO2e)
0	6825	0	0%	0%	100%	6825	4%	0%	0%	104%	7109
1	6825	0	1%	0%	101%	6881	4%	0%	0%	104%	7109
2	6825	0	2%	0%	102%	6967	4%	0%	0%	104%	7109
3	6825	0	3%	0%	104%	7085	4%	0%	0%	104%	7109
4	6825	0	5%	0%	106%	7237	4%	0%	0%	104%	7109

5	6825	0	8%	1%	109%	7429	4%	0%	0%	104%	7109
6	6825	0	10%	1%	112%	7665	4%	0%	0%	104%	7109
7	6825	0	13%	1%	117%	7952	4%	1%	0%	105%	7168
8	6825	0	17%	1%	122%	8301	4%	2%	0%	106%	7257
9	6825	0	21%	1%	128%	8723	4%	3%	0%	108%	7380
10	6825	0	25%	2%	135%	9238	4%	5%	0%	110%	7539
11	6825	0	29%	2%	145%	9869	4%	8%	1%	113%	7738
12	6825	0	34%	2%	156%	10652	4%	10%	1%	117%	7984
13	6825	0	40%	3%	171%	11640	4%	13%	1%	121%	8283
14	6825	0	45%	3%	189%	12912	4%	17%	1%	127%	8647
	96					123	MTCO2e				105

Modified Low Corrosivity Case

Year	Indirect Emissions - Original TEWI Calculation (kgCO2e)	δ_coat uncoated	δ_corr uncoated	δ_charge uncoated	γ Uncoated	Indirect Emissions CO2e Non-Coated (kgCO2e)	δ_coat Corrosion Protection	δ_corr coated	δ_charge coated	γ Coated	Indirect Emissions CO2e - Coated (kgCO2e)
0	6825	0	0%	0%	100%	6825	4%	0%	0%	104%	7109
1	6825	0	0%	0%	100%	6828	4%	0%	0%	104%	7109
2	6825	0	0%	0%	100%	6833	4%	0%	0%	104%	7109
3	6825	0	0%	0%	100%	6840	4%	0%	0%	104%	7109
4	6825	0	0%	0%	100%	6850	4%	0%	0%	104%	7109
5	6825	0	0%	1%	101%	6861	4%	0%	0%	104%	7109
6	6825	0	0%	1%	101%	6874	4%	0%	0%	104%	7109

7	6825	0	0%	1%	101%	6889	4%	0%	0%	104%	7113
8	6825	0	1%	1%	102%	6960	4%	0%	0%	104%	7118
9	6825	0	2%	1%	103%	7061	4%	0%	0%	104%	7125
10	6825	0	3%	2%	105%	7195	4%	1%	0%	105%	7165
11	6825	0	5%	2%	108%	7365	4%	2%	1%	107%	7286
12	6825	0	8%	2%	111%	7576	4%	3%	1%	109%	7416
13	6825	0	10%	3%	115%	7833	4%	5%	1%	111%	7582
14	6825	0	13%	3%	119%	8144	4%	8%	1%	114%	7790
	96MTCO_2e					100 MTCO_2e					101 MTCO_2e

APPENDIX B

NIST CYCLE_D-HX Model Data:

System Cooling Capacity: 11.81kW
Compressor power: 2.208 kW
Compressor COP: 5.349
Refrigerant: R410A

Table 3: Thermodynamic States of Cycle_D-HX

STATE	T	P	H	V	S	XQ
	(C)	(kPa)	(kJ/kg)	(m^3/kg)	kJ/(kg	C)
Compr. Shell Inlet	14.7	1074	429.8	2.51E-02	1.81272	1
Cylinder Inlet	14.7	1074	429.8	2.51E-02	1.81272	1
Cylinder Outlet	65.8	2440.9	462.3	1.23E-02	1.84178	1

Condenser Inlet	65.8	2440.9	462.3	1.23E-02	1.84178	1
Cond. Sat. Vapor	40.4	2440.9	425.2	9.57E-03	1.72765	1
Cond. Sat. Liquid	39.6	2399.8	265.5	1.02E-03	1.21844	0
Condenser Outlet	34.6	2399.8	256.2	9.89E-04	1.18831	0
Exp. Device Inlet	34.6	2399.8	256.2	9.89E-04	1.18831	0
Evaporator Inlet	10.3	1096.5	256.2	5.28E-03	1.19831	0.193
Evap. Sat. Vapor	9.7	1074	423.9	2.41E-02	1.79185	1
Evaporator Outlet	14.7	1074	429.8	2.51E-02	1.81272	1

APPENDIX C:

Additional Figures for Calculations

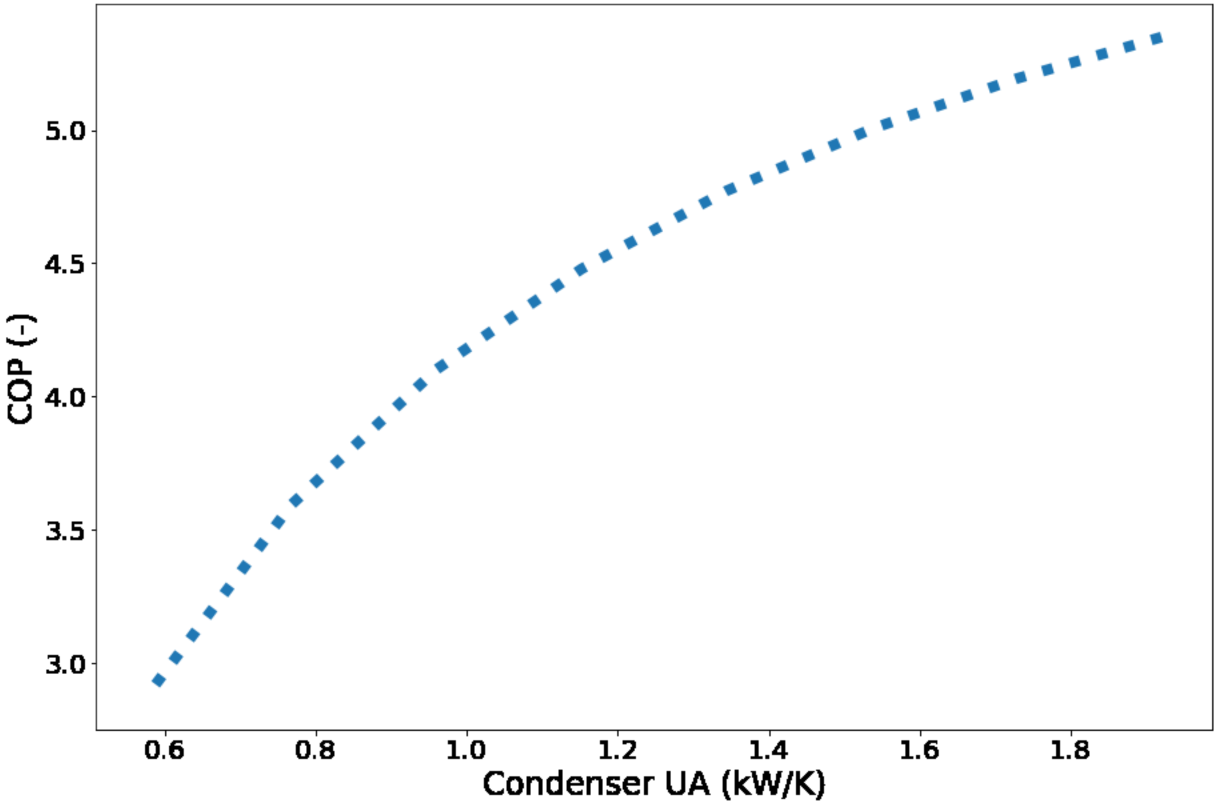

Figure 9: COP Degradation with Decreasing UA

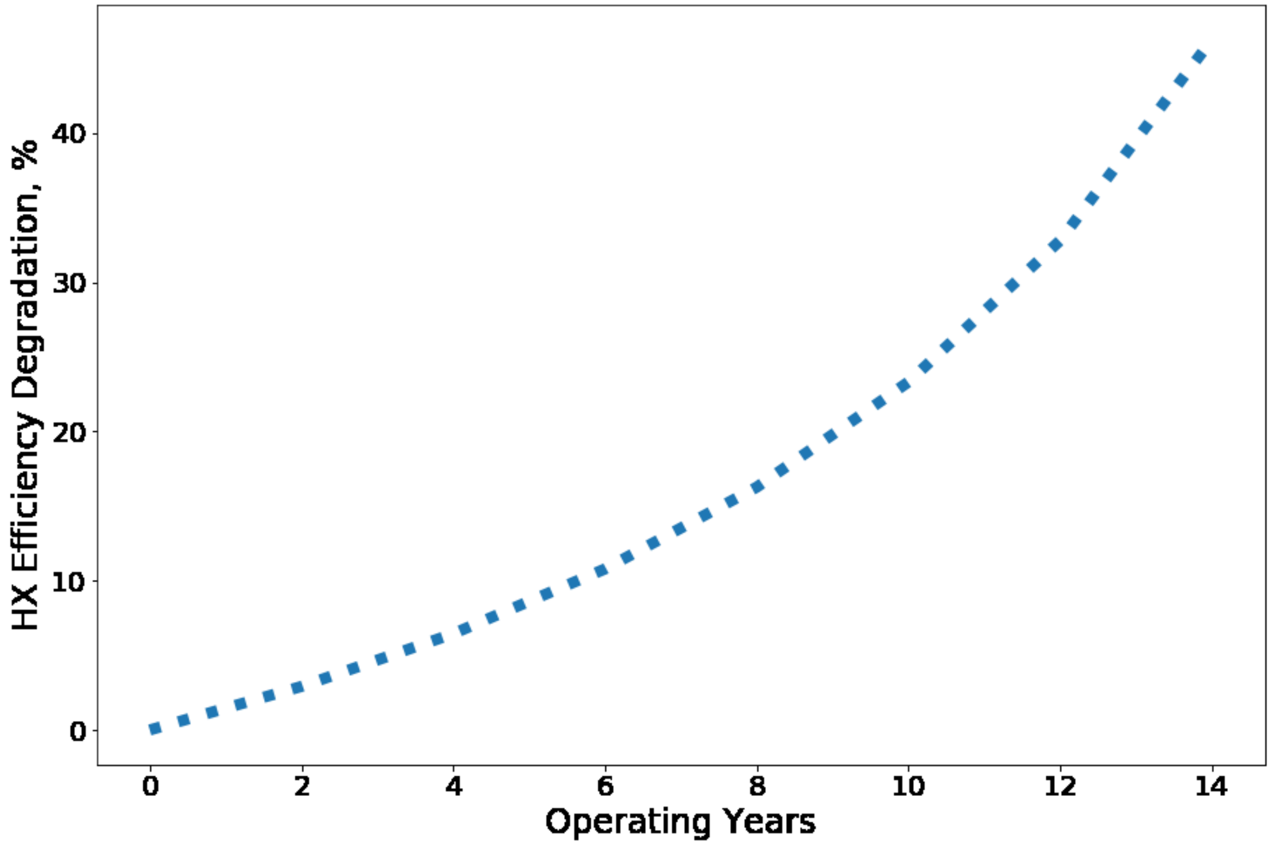

Figure 10: Heat Exchanger Efficiency Reduction over Lifetime

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