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# COMPARATIVE LCA

## HYDROMX, PROPYLENE GLYCOL, AND INHIBITED WATER AS HEAT TRANSFER FLUIDS


**PREPARED BY:**

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This analysis and report was prepared for Hydromx Inc. by Ecoform, an environmental consulting firm committed to the design, evaluation, and adoption of clean products and materials through technical and policy research.

Results and conclusions of this report are based on data provided to Ecoform by Hydromx, Inc and its suppliers. This analysis would not have been possible without the cooperation of individual Hydromx, Inc customers who voluntarily provided case study data and confidential business information in support of this effort. Ecoform staff would like to thank Hydromx, Inc and its partners for their cooperation and assistance in this analysis. Please direct any questions or enquiries about this report to the following:

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# 1 OVERVIEW OF LCA STUDY AND GOALS

Hydromx, USA is a leading manufacturer of an innovative, nano-technology based heat transfer fluid (HTF) for closed circuit heating and cooling systems. Utilizing a proprietary nano-technology based formula, HydromxPG® (Hydromx) makes use of proprietary nano-particles to increase the overall surface area available for heat transfer, resulting in higher heat transmission and an overall decrease in system energy consumption. Hydromx is a drop in replacement for typical water- and glycol -based fluid systems. Hydromx is manufactured to International standards such as ISO 9001:2008, ISO 14001:2004, ISO 22000:2005 and OHSAS 18001:2007.

To assess the overall environmental performance of their nano-technology based fluid, Hydromx USA has commissioned this LCA study to evaluate the performance of Hydromx along with other traditional heat transfer fluids (HTFs) under different scenarios. This report documents the specifics of that study along with analysis of the results.

## 1.1 Goals of the LCA

The goal of this study is to evaluate the comparative life cycle impacts of the Hydromx heat transfer fluid as well as those of traditional inhibited water and propylene glycol-based mixtures under two common use scenarios: Residential/Office and Data Centers. Additional goals are to inform future product improvement by Hydromx, USA and to evaluate the relative contributions of the use phase to the overall lifecycle impacts for heat transfer fluid such as Hydromx. This LCA was performed in conformance with ISO 14040/14044, the Environdec PCR for Efficient Heat Transfer Fluids for Heating and Cooling (2017-04), and the associated NSF Addendum to Environdec Heat Transfer Fluid PCR – North America.

## 1.2 Intended Application

Results of the study will be used internally to support future product improvement, and to inform the creation of an EPD for external communications. Though none are planned at this time, this study may also be used to support future comparative environmental claims made by Hydromx, USA.

## 1.3 ISO 14040/44 and PCR Compliance

This LCA has been conducted in conformance to the following guidance documents:

- ISO 14040 and ISO 14044,
- ISO 21930 (2007), and
- International EPD program PCR for Heat Transfer Fluids and NSF Addendum (2019)

As required by ISO, this analysis has been critically reviewed by a third party and found to be compliant with the above guidance.

## 1.4 Commissioner of LCA and Practitioner

This LCA study was commissioned by Hydromx, USA. Ecoform, LLC was contracted to conduct the LCA modeling of the HTFs and to document the results of the study in this LCA background report and subsequent EPD. Jack Geibig, President of Ecoform served as the project manager for this analysis.

## 1.5 Reporting Date

This LCA was conducted in 2019 and a draft report was prepared for review in May, 2019. The final report was completed and published in December, 2019.

### 1.6 Intended Audience

The intended audience for this LCA report is for internal product development by Hydromx, USA, and for use in external business-to-business communications through the publication of an EPD.

### 1.7 Comparative Assertions

This study is intended to evaluate the comparative environmental performance of the various HTFs under typical scenarios. As such, this LCA may be used to provide the foundation for future comparative claims made between Hydromx-based fluids and traditional inhibited water and propylene glycol-based fluids. As required by ISO 14044, this analysis has undergone a thorough review by an external panel of experts.

### 1.8 LCA Tool and Data

The inventory for the LCA study is based on the 2018 production figures for Hydromx, at the Hydromx, USA production facility in New York, U.S. The accuracy of the data provided for the purposes of the study is the liability of Hydromx, USA. This LCA was modeled with GaBi 9.2 package using Service Pack 39, the latest version of the GaBi database and impact factors.

### 1.9 Required Statements

This LCA has been conducted in accordance with ISO 14040/14044 and ISO 21930:2007. In order to support comparative assertions, this LCA is intended to support the production of an EPD that meets all comparability requirements stated in ISO 14025:2006. Comparability of EPDs is limited to those applying a functional unit. However, differences in certain assumptions, data quality, and variability between LCA data sets may still exist. As such, caution should be exercised when evaluating EPDs from different manufacturers or programs, as the EPD results may not be entirely comparable. Any EPD comparison must be carried out at the construction works level per ISO 21930:2017 guidelines. The results of an EPD related to this report reflect an average performance by the product and its actual impacts may vary on a case-to-case basis

## 2 PRODUCT DESCRIPTION

### 2.1 Heat Transfer Fluids

Due to its low cost and wide availability, water is the most commonly used heat transfer fluid in the world in heating and cooling systems. It is also a relatively good fluid for facilitating heat transfer in climate control systems. However, the use of water as a heat transfer fluid has limitations. For example, the high freezing temperature of water makes it unsuitable for use in colder climates where freezing can occur. Also, the use of water can facilitate corrosion in some systems, making the use of a chemical inhibitor additive a necessity. Despite these limitations, water remains a popular choice for most applications due to its wide availability and low cost.

Glycol-based fluids are used in heat transfer applications in the form of Ethylene Glycol or Propylene Glycol. The choice of one or the other may be defined by local requirements and/or specific applications. However, in most heat transfer applications propylene glycol-based fluids are the best choice among the glycols because of their superior heat transfer efficiency, their overall low viscosity, and relatively benign nature as compared to their ethylene-based counterparts. Glycol-based heat transfer solutions are preferred over water in cold climates due to its ability to function at below freezing temperatures.  Propylene glycol heat transfer fluids are typically sold as product concentrates to be diluted to the desired concentration according to the needs of the system and climate conditions at the location.   However, propylene glycol-based HTFs also have limitations, due largely to its higher viscosity, resulting in a loss of heat transfer efficiency when compared to water of up to 10%.

Water- or propylene glycol-based fluids are routinely supplemented with chemical inhibitors, a category of chemical additives designed to inhibit corrosion and scale build-up in a system.  While inhibitors can be comprised of a variety of chemicals, they typically fall into a few basic categories based on the overall use and conditions of the system.  For this analysis, a phosphate inhibitor was evaluated for both the water and propylene glycol HTFs due to its compatibility with these HTFs, and the availability of existing lifecycle data.[1,2] Concentrated propylene glycol products typically contain 2-5% inhibitor content in the concentrate, while for systems using water a phosphate inhibitor is typically added during installation to achieve a system concentration of between 1-3%.

Unlike typical HTFs, Hydromx® is a revolutionary heat transfer nanofluid that utilizes Nano-Thermo™ technology. Hydromx® uses nano-particles that are suspended in a stable state to increase the speed of heat transfer, by heating up (or removing heat from) the fluid and transferring energy in a shorter amount of time when compared to traditional water-based systems, thereby requiring significantly less energy.  No matter what the energy source, or how efficient the boiler or chiller is, Hydromx® improves the efficiency of the whole system by transferring energy more effectively.

Furthermore, Hydromx® is formulated with inhibitors that prevent corrosion, calcification and algae in the systems. It is certified under the BuildCert Chemical Inhibitor Approval Scheme to inhibit corrosion of metallic and plastic parts, and prevent scaling up of the system, particularly the boiler.


**Figure 1 - Hydromx 250 Gal Tote (945 L)**

This study evaluates the life-cycle performance of each of these HTFs, specifically, inhibited water, propylene glycol, and Hydromx.  The in-use system composition of each HTF is presented in Section 2.4, Table 1.

1 Dowfrost MSDS, accessed online Sep 9, 2019.  http://www.chemworld.com/v/vspfiles/assets/images/sds-dowfrost.pdf

2 Arctik Snow MSDS, accessed online Sep 9, 2019.  https://www.g2solutionsco.com/wp-content/uploads/Arctik-Snow-30-96-I-SDS-FINAL.pdf

## 2.2 Mechanisms of Heat Transfer in Fluids

The mechanisms of heat transfer in fluids are complicated and are the subject of entire books. While it is beyond the scope of this study to describe these mechanisms in detail, the discussion that follows is an attempt to provide a brief explanation for how the addition of nano particles to an HTF can aid in the overall performance of the system.

To gain an understanding of the merits of different HTFs, it helps to first understand how fluids behave. The behavior of fluids were once described by Sir Isaac Newton, who observed that most fluids have a constant flow, or viscosity, that changes only with changes in pressure or temperature. One such fluid is water, which when heated with increasing temperature will eventually turn to a gas (steam), or when cooled below 32 degrees Fahrenheit will become a solid. However, between these two extremes, water essentially behaves the same regardless of temperature. Such fluids are referred to as Newtonian fluids.[3]

Some fluids, however, behave differently, responding to conditions of stress by exhibiting a change in viscosity. These fluids are often referred to as Non-Newtonian fluids. A notable example of one such fluid is a mixture of cornstarch and water, which despite flowing like water when poured, will stiffen significantly while being stirred. Fluids that respond to physical shearing by thickening such as with cornstarch are referred to as Rheopectic fluids.[4]

Heat transfer in fluids is typically achieved primarily through convective or conductive heat transfer. Convective heat transfer is defined as the heat transfer due to the bulk movement of molecules in liquids.[5] Low viscosity fluids maximize the convective transfer of heat by circulating more rapidly through the system. The rapid circulation allows molecules to cycle through the heat/cool cycle at a greater rate, increasing the effectiveness of the heat transfer.

However, Non-Newtonian fluids make use of a second form of heat transfer, conduction. Conductive heat transfer is the transfer of heat through the collision of particles. When put under stress caused by the turbulence experienced under non-laminar flow conditions, the space between molecules will tighten, increasing the viscosity of the fluid, and thereby increasing the heat transfer that occurs through conduction.[6] When compared to the other traditional HTFs, the much higher specific surface area of the nanoparticles has the effect of enhancing the cumulative heat transfer of the convective and conductive mechanisms.

A study of the properties of Hydromx commissioned from an independent laboratory[7], sought to evaluate the performance of Hydromx compared to water, and ethylene glycol, another type of HTF

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[3] RheoSense. Accessed on Sept 9, 2019. https://www.rheosense.com/applications/viscosity/newtonian-non-newtonian

[4] Science learning hub. Accessed on Sep 9, 2019. https://www.sciencelearn.org.nz/resources/1502-non-newtonian-fluids

[5] Wikipedia, Accessed on Sep 9, 2019. https://en.wikipedia.org/wiki/Convection

[6] Wikipedia, Accessed on Sep 9, 2019. https://en.wikipedia.org/wiki/Thermal_conduction

[7] Assael, M. Hydromx Properties Investigation. November 2013 http://www.galaxyens.com/reports-certificates/HYDROMX_PROPERTIES_INVESTIGATION_REPORT.pdf

similar to propylene glycol. The study conducted tests to determine key physical properties of the nano-fluid, and to assess the performance of Hydromx relative to other HTFs for both convection and conduction heat transfer under controlled laboratory conditions. Among the conclusions, the author highlighted the following:

1. When compared to water above zero degrees Celsius, Hydromx exhibited convective heat transfer almost double that of water despite a much lower thermal conductivity. This despite the fact that the testing was done in a static vessel. The author concludes that this is likely due to the "enhancement of the heat transfer attributed to the nanoparticles" and that the "nanofluid is likely to be much better in real applications" under turbulent flow.
2. When compared to a 50% mixture of ethylene glycol and water, (another glycol-based HTF), Hydromx displayed a nearly identical thermal conductivity to the ethylene based alternative in lab testing. However, the author concludes that the nanoparticle fluid is expected to carry heat better in real applications because of its much lower viscosity.

The above study characterized the performance of the HTFs in a simple laboratory testing. However, characterizing the thermal and physical mechanisms of an HTF in an operating system can be difficult due to the complexities of the fluid's movement in a constrained environment. In real world applications, heating or cooling in a system occurs under forced turbulent flow conditions, characterized by flows with a Reynolds number of over 4,000. During turbulent flow, micron level vortexes (i.e. eddies) are created. Eddies mostly occur vertical to the flow and slow the convective thermal transfer in Newtonian fluids. However, with nanofluids such vortexes act to enhance the interaction between nanoparticles, which in return, improves the conductive transfer of heat, and the overall mass thermal properties of the fluid.

For additional information on this subject, please consult the citations listed or a more comprehensive text on fluid mechanics experienced under turbulent flow.

## 2.3 HTF Composition

HTFs are often sold as concentrates designed to be diluted with water at installation to meet the specific requirements of the designed system. The amount of dilution required to form the desired HTF mixture can vary depending on the range of conditions experienced at the location (e.g. sub-zero temperatures), the purpose of the heat transfer system, and the expected operating parameters. Dilution is typically performed with tap, deionized, or distilled water, depending on the parameters of the specific HTF concentrate.

The compositions of each of the HTFs evaluated in this study are presented in Table 1. These compositions reflect the mixtures created after dilution during the installation of the HTF (sometimes referred to "as used"), and include the presence of inhibitors as described in Section 2.1.

**Table 1. Composition of HTF Mixtures after Dilution (wt%)**

| Components | Hydromx | Inhibited Water | Propylene Glycol |
|---|---|---|---|
| Water | 65% | 97% | 58.3% |
| Propylene glycol | 26% | - | 40% |
| Glycerine | 3% | - | - |
| Sodium molybdate dihydrate | < 1% | - | - |
| Triazole | < 0.5% | - | - |
| Potassium Phosphate | - | 3% | 1.7% |
| Nano additives (proprietary) | < 5% | - | - |

To achieve the above mixtures, Hydromx and propylene glycol HTFs both require dilution at installation. For Hydromx, the manufacturer specifies a 50% dilution of the concentrate in all circumstances. Similarly, the propylene glycol-based concentrate was diluted with water to create a 40% glycol content in the resulting HTF mixture, a concentration capable of meeting the demands of locations across most of the continental US.[8]

Unit process flows for each of the HTFs evaluated are presented in Appendix B. A complete bill of materials is given per 1 square meter of temperature-controlled space for each of the scenarios evaluated, along with the cumulative energy consumption over the evaluated period of use.

## 2.4 Technical data of HTFs

Technical data for the HTFs evaluated in this study are presented in the Table 2. Additional technical data for Hydromx is presented in Appendix E.

**Table 2 HTF Mixture Technical Data (as used)**

| Tech Specs | Hydromx (50%)[a] | Inhibited Water | Propylene Glycol (40%)[b] |
|---|---|---|---|
| **Color** | Blue | Clear | Green |
| **pH** | 8.20-8.80 | 7 | 6.0-8.0 |
| **Freezing Point** | - 47°C | 0°C | - 35°C |
| **Boiling Point** | 120°C | 100°C | 105°C |
| **Density (kg/L)** | 1.065 | 0.998 | 1.055 |
| **Viscosity (cP) (at 20°C)** | 7.2 | 1 | 18.5 |

[A] Hydromx data sheet. Accessed on-line on June, 22, 2019. www. Hydromx.com
[B] Dowfrost Engineering and Operating Guide. p.9. www.dow.com

[8] Dowfrost Engineering and Operating Guide. p.9. Accessed on Sept 9, 2019 at https://www.dow.com/en-us/document-viewer.html?ramdomVar=6633862461868932376&docPath=/content/dam/dcc/documents/en-us/app-tech-guide/180/180-01286-01-engineering-and-operating-guide-for-dowfrost-and-dowfrost-hd.pdf

## 2.5 Applicability

HTFs are commonly used in closed-loop heating and cooling systems designed to control the interior temperature of buildings. All of the HTFs are drop in replacements for one another within a given system or location.

# 3 LIFE-CYCLE ASSESSMENT SCOPE

## 3.1 Life-Cycle Approach

Life-cycle impacts in a variety of human health and environmental categories were evaluated for buildings using HTF-based systems. To facilitate comparisons, three separate HTFs were evaluated under similar use conditions using two typical building scenarios: residential/office and data centers. Each of these scenarios was based on case study data collected under real world conditions. A description of each of these scenarios is presented in Section 3.3.3 and in Appendix B. For each scenario, the impacts associated with the production, transportation, use, and ultimate disposal of Hydromx and other alternative HTFs were calculated to evaluate their environmental and human health impacts. The results were then used to evaluate their comparative performance.

The life-cycle analysis was performed using version 9.2 of the GaBi Life-Cycle Software. Primary data were collected and used for all processes controlled by Hydromx, USA. Data for the remaining lifecycale processes for Hydromx and for the other HTF alternatives were sourced from publicly available secondary data from GaBi and Ecoinvent. Specific life cycle inventory metrics and impact categories evaluated are presented in Section 4.1. A listing of all data inventories are presented in Appendix A. Assumptions and uncertainties associated with this study are presented in Sections 5.4 and 5.5.

## 3.2 Functional Unit and Reference Service Life

A functional unit is defined by ISO 21930:2007 as the quantified performance of a product system for a building product that is used as a reference unit in an EPD based on LCA. For HTFs, the functional unit shall be 1 square meter of temperature-controlled floor space, as required by the NSF addendum to the International EPD system PCR for Heat Transfer Fluids.

Heat transfer systems in buildings are uniformly closed loop, preserving the contained HTF for long durations of time. HTF's are seldom replaced except in the case of system failure, repair resulting in loss of fluid, or leakage. However, they are periodically rebalanced chemically to maintain performance. As a result, all of the HTFs are considered to have a reference service life of 20 years.

## 3.3 System Boundaries

The system boundary for this Cradle-to-Grave study is depicted in the diagram below. Individual life cycle modules are discussed in further detail later in this section. All significant environmental aspects in the life-cycle were in scope and evaluated. Overall, this scope breaks down the life-cycle into the following stages: product manufacturing, design and installation, product use, and end-of-life. Stages are further broken down and reported by modules.

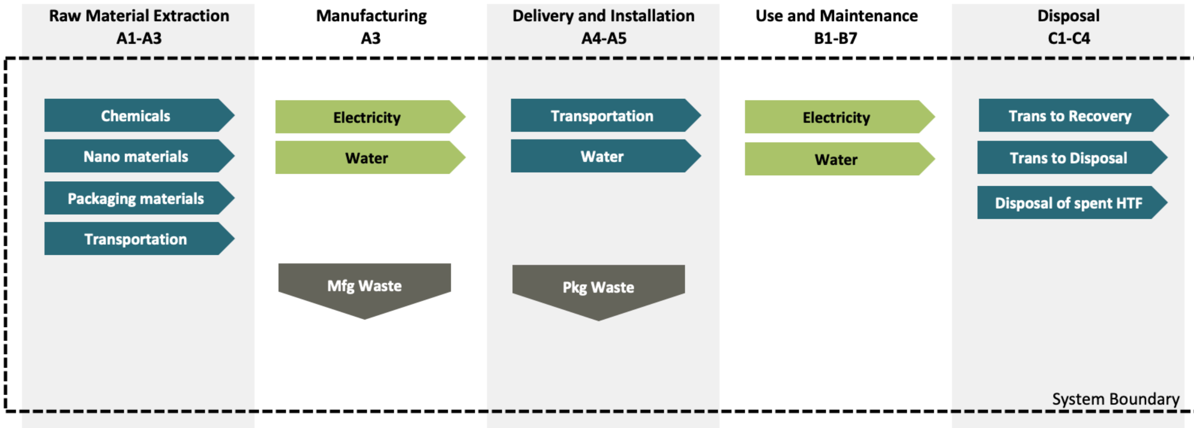


**Figure 2. System Boundary of Analysis.**

### 3.3.1 Product Stage (A1-A3)

This stage considers the upstream extraction and processing of raw materials, transportation of the materials to the site of manufacture, and the manufacturing of the product itself. Specifically, this included:

- Extraction and processing of raw materials
- Generation of water and energy inputs
- Manufacturing of packaging materials required for transport
- Transportation of materials to the manufacturer gate
- Waste generated during materials processing
- Manufacturing of the product
- Waste generated during manufacturing, including packaging waste.

Raw materials used in the manufacturing of each HTF were identified through the creation of a bill of materials for each alternative. All elementary flows at resource extraction are included in this study. Established secondary data sets were then identified and used to model each of the HTFs. Secondary data for this project were all sourced from the latest versions of either the GaBi Professional or Ecoinvent databases, as appropriate. Specific data sets used in this study are listed individually in Appendix A, and are assessed independently for quality in Section 3.7.

Raw materials for Hydromx were obtained from a variety of sources regionally. All sources are within a 100-mile radius of its manufacturing facility located in New York, and were transported by truck to the manufacturing site. Transportation was modeled using secondary transportation data from GaBi at a distance estimated for each ingredient supplier. Since propylene glycol is also a component of the Hydromx fluid, it was assumed that the propylene glycol for the propylene glycol HTF was also obtained from the same supplier under the identical transportation scenario. Water used for dilution or as the basis for the inhibited water HTF is typically obtained from local tap water and so no transportation was calculated. Both the production of water and the treatment of spent HTF discharges were considered intermediate flows and thus modeled.

Hydromx is manufactured using a simple mixing process. Raw materials are first dispensed in the required quantities into a tank, mixed together, and finally packaged for sale and shipment. There is no waste product generated during the manufacturing of the product. The concentrated Hydromx solution is then diluted 50/50 on-site with water during installation to form the Hydromx HTF mixture given in Table 1. Product manufacturing data was obtained directly from Hydromx for the year 2018 production.

Propylene glycol HTFs are also manufactured using a similar mixing and packaging process to that of Hydromx. However, primary data for the manufacturing of propylene glycol HTFs was not directly available for evaluation. Given that the processes utilized by Hydromx, USA are typical for the manufacture and packaging of simple chemical mixtures, the data obtained from Hydromx was considered representative and thus used to evaluate the propylene glycol HTF. No manufacturing was necessary or modeled for the water HTF, as mixing of the inhibitor with the water is done during installation within the heat transfer system.

Hydromx is primarily shipped in Intermediate bulk container (IBC) totes, surrounded by a reinforced galvanized steel cage. A picture of the packaging is displayed in Figure 1. Although this packaging is routinely returned and reused for future orders, the packaging was evaluated in this analysis as required by the PCR. It was assumed in this analysis that similar packaging was used for the propylene glycol HTF.

**Table 3. Material Composition of Reusable IBC Totes- 945 L (250 Gal)**

| Components | Mass |
|---|---|
| HDPE | 37.1 kg |
| Galvanized steel | 18.5 kg |

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Energy inputs for Hydromx were based on the production of energy in the New York region of the country. Production of the propylene glycol HTF was modeled using the US energy grid since the manufacturing location could be any region in the US.

### 3.3.2 Delivery and Installation (A4-A5)

Delivery of Hydromx concentrate to the site is typically done by truck, but can also be shipped internationally. A transportation distance of 620 miles was used as a basis for the transportation modeling to site, as suggested in the PCR.

Installation involves draining the system of previous fluid used for heat transfer, if any, and then flushing and refilling the system with the HTF of choice. During installation, the Hydromx concentrate is diluted to a mixture of 50% Hydromx and 50% tap water. Likewise, the propylene glycol-based HTF is also diluted with tap water to achieve a 40% concentration of propylene glycol, while the inhibited water HTF is created by adding a chemical inhibitor to water to achieve a 3% system inhibitor concentration.

Typically, the heating or cooling system already exists, and as such the system and its construction are outside of the scope of this study.

### 3.3.3 Use Stage (B1-B7)

Use stage modules include the use, maintenance, repair, and replacement of the product if it becomes necessary. For the use of HTFs, this specifically includes:

- Energy consumed during the operation of the heating or cooling system
- Maintenance of the HTF composition and volume.

To assess the energy consumed during the operation of the system attributable to HTFs, two distinct scenarios were evaluated:

- Residential/office
- Data control center.

The scenarios were chosen to represent specific use sectors for HTFs. These scenarios differ in occupant usage, hours of expected heating or cooling system operation, and other important factors. Key parameters for each of the scenarios are presented in Table 4.

**Table 4. Life-Cycle Scenarios – Building Types**

| Parameter | Life-Cycle Evaluation Scenarios | |
|---|---|---|
| | Residential/Office[a] | Data Center[b] |
| **Total Facility Size** (m$^2$) | 200 | 350 |
| **Energy Use** (kWh/yr) | | |
| – **Hydromx** | 10,300 | 122,200 |
| – **Glycol/Water** | 14,920 | 176,900 |
| – **Water** | 13,500 | 160,000 |
| **Period of Operation** (yr) | 20 | 20 |
| **Volume of System** (liters) | 140 | 2,400 |
| **System Operation** (hrs/day) | 8 | 24 |

[a] Scenario based on profile of typical US home consumption , US Energy Information Administration, 2016.
[b] Data center scenario based on HBO Case study in Appendix B.

The residential scenario was based on the US Energy Information Administration profile of typical US home energy consumption in 2016, while a case study of a Home Box Office (HBO) facility served as the basis for the data center scenario. Use phase energy consumption values for traditional HTFs were calculated using well-established engineering factors, while a series of in-field case studies were used to establish energy use values for Hydromx. Additional details on the development of these scenarios including a listing of individual case studies conducted, a complete bill of materials (BOM) for each HTF by scenario, and sample calculations for process inputs are presented in Appendix B. Energy consumed during the Use phase of the life-cycle was modeled using the national US Energy grid.

Maintenance of the HTF involves periodically checking the level and quality of the HTF and making adjustments when necessary. Adjustments typically involve either adding fluid to restore lower levels due to inadvertent system leakage, or rebalancing the composition of the fluid should it have degraded somewhat. Degradation can occur from volume loss, or from reactions involving the formation of scale or small amounts of sludge over time. Such rebalancing occurs rarely and the volume of chemical used during such balancing is minimal and deemed insignificant to this study. However, as a placeholder, a 0.1% volume use per year was factored in to the analysis to account for such potential activities.

Heat transfer fluids do not typically require replacement or repair over the lifetime of the system, unless a system failure occurs. As such, these modules are not evaluated in this analysis. Due to the closed nature of typical heating and cooling systems, and the composition of HTFs, no significant emissions attributable to the use of HTFs occur during the use phase.

### 3.3.4 End of Life (C1-C4)

HTFs are not typically disposed unless there is a leak, contamination, or a change in the type of fluid is made. Rather, during system operation the fluid level and quality are periodically checked and adjustments made when necessary as described in Section 3.3.2.

Should a system be drained (e.g. during retrofit or replacement), fluid is typically captured and retained for later use. Should the fluid be deemed at end-of-life, it may be disposed of according to manufacturers guidance. In this analysis, both the propylene glycol-based HTF and Hydromx were considered to undergo treatment at EOLF as a hazardous waste, while the inhibited water HTF was disposed safely to drain. Transportation to treatment was modeled, where appropriate, but was not required for the inhibited water.

### 3.3.5 Benefits Beyond the Boundary (D)

No benefits beyond the boundary are claimed or modeled in this LCA.

## 3.4 Cut-Off Rules

The cut-off criteria for all activity stage flows considered within the system boundary conform with Section 4.2.3 of the reference PCR. Specifically, the cut-off criteria were applied as follows:

- All inputs and outputs for which data are available are included in the calculated effects and no collected core process data are excluded for any of the HTFs evaluated.
- All energy and material inputs, including packaging, have been assessed in this analysis, as required in the PCR.
- Hydromx and the alternative HTFs do not contain any intentionally added content that is required to be reported by regulation.

Categorical exclusions include the following omitted processes:

- Human activity and personnel related activity (eg. Travel, office operations)
- Capital goods and infrastructure

- Heating/cooling system equipment containing the HTFs.
- Energy and water use related to company management or sales activities

## 3.5 Allocation Procedures

There are no co-products in the production of Hydromx, therefore co-product allocation was not performed. Transportation of raw materials purchased by Hydromx is allocated by source according to mass purchased. For the manufacturing of Hydromx, no allocation for energy or water consumption was made as the manufacturer provided the product specific data. For comparison purposes, allocation for propylene glycol used in glycol/water mixtures is performed in manner consistent with the allocation procedures for Hydromx. Allocation of any recycled or recyclable materials is made following the Polluter Pays Principle. All other allocation procedures used in the study were consistent with those required for ISO 14040/14044.

## 3.6 Data Collection and Treatment of Missing Data

Data were required to inform this assessment of HTFs. For Hydromx, primary data were used for all processes under direct control of the company, representing 2018 data. Where available, supplier data was used for raw materials used in the manufacture of the product. If not available, secondary data from the 2019 release of the GaBi database, or from Ecoinvent version 3.5 were used. Secondary data were used for all non-production stages.

Both the propylene glycol–based and inhibited water HTFs were assessed using product formulations derived directly from publicly available data for actual products. Both formulations, as stated, are typical of formulations currently used in heat transfer applications within the marketplace, and as such are considered representative products within the class. Given that the collection of primary data for these representative products was not possible, industry average data were used to characterize product manufacture. See section 3.3.1 for additional details.

Hydromx use stage data were drawn from a collective set of case studies from actual installations, shown in Appendix B. These data were used to construct and inform scenarios to model the use phase, the creation of which are described in detail in Section 3.3.3 and Appendix B.

Some of the HTFs evaluated contained chemicals for which no life-cycle inventory data exist. In such cases, chemicals were modeled by using surrogate (or proxy) chemicals chosen for their structural similarity, similar function, and where possible using chemicals that mimic the process by which they are synthesized. If no suitable surrogate is identified, as a last resort an average inventory profile from other chemicals that serve an identical function (e.g. non-ionic surfactants) was determined. Specific chemicals for which proxy data were used are identified and discussed further in this section.

### 3.6.1 Nano Materials

There are no publicly available data for carbon nano materials similar to those utilized in Hydromx. A search of existing publicly available databases, and inquiries to ThinkStep for data available for purchase failed to identify any such material inventories. A search of published LCA research also failed to identify a study utilizing inventories of carbon-based nanoparticles similar to those used in the fluids.

In lieu of such data, carbon black was selected as a proxy based on the following:

- It is made from the same material (carbon) as used in the nano materials.
- Size of carbon black (8-100 nm)[9] is similar to that of carbon nano particles (1-100 nm)[10]
- Both are made using energy intensive processes.

No other potential proxy was identified as suitable, given the relative lack of inventory data for such materials. Mass of the materials was assumed to be similar.

### 3.6.2 Potassium Phosphate

There are no available data specific to the production of potassium phosphate, so it was modeled. The production of potassium phosphate is described from the following equation:

$$(NH_4)_3PO_4 + 3KCl \rightarrow K_3PO_4 + 3NH_4Cl$$

The molecular weights of the compounds are 149.09 g/mol for ammonium phosphate, 74.55 g/mol for the potassium chloride, and 212.27 g/mol for potassium phosphate.

The production of potassium chloride can be found in the Fertilizers Europe database (in GaBi):

- Potassium chloride (KCl/MOP, 60% K2O), agg

The production of ammonium phosphate can be found in the Gabi database as:

- Diammonium phosphate (DAP, 18%N, 46% p2O5), agg

The unit processes can be represented as:

**Table 5. Modeling of Potassium Phosphate**

| | Process/Material | Amount | Units |
|---|---|---|---|
| **Outputs** | Potassium phosphate (modeled) | 212.27 | kg |
| **Inputs** | Diammonium phosphate (DAP, 18%N, 46% p2O5), agg | 149.09 | kg |
| | Potassium chloride (KCl/MOP, 60% K2O), agg | 223.65 | kg |

[9] AdityAberla, Carbon Black 101. Accessed online Sep 9, 2019 at https://birlacarbon.com/whats-trending/carbon-black/

[10] Advanced Microanalytical, Nano and nanoparticle testing lab. Accessed on Sep 9, 2019 at https://www.advancedmicroanalytical.com/AMAServices.aspx?mode=serv&ID=23&bcl=2&gclid=Cj0KCQjwuNbsBRC-ARIsAAzITufYXCb0oV6IAE9kntpP9nbtnljecvw48J8x4U-SEyDCdyVTOzbSFncaAixqEALw_wcB

### 3.6.3 Sodium Molybdate

There are no available data specific to the production of sodium molybdate. It was also not possible to model sodium molybdate directly from existing datasets as there are no available life-cycle inventories for chemicals containing molybdenum. As such a proxy was sought.

Sodium molybdate serves as an inhibitor for corrosion. Potential proxies include those suitable for use in heat transfer systems. After a search of available life-cycle datasets was performed, no existing data specific to compounds used for corrosion inhibition compounds were identified. As such, it was determined that potassium phosphate would be the most suitable proxy for Sodium molybdate in the Hydromx HTF, for the following reasons:

- Potassium phosphate is a commonly used corrosion inhibitor for glycol-based HTFs, including Hydromx.
- The molecular weight is similar to that of sodium molybdate.
- No other potential proxy was identified as suitable, given the relative lack of inventory.

The modeling of potassium phosphate is described in Section 3.7.2. The molecular weight of potassium phosphate is 212.27 g/mol while the molecular weight of sodium molybdate is 205.92 g/mol. The Inventory input was adjusted to account for the difference in mass before input into the model.

## 3.7 Data Quality Requirements and Assessments

Individual data used in this analysis are assessed following the requirements of ISO 14040/14044 [4],[5] and ISO 21930:2017 [6] as required by the International EPD Program PCR [2], which require the inventory data to be as representative (technologically, geographically, and time-specific), complete, consistent, reproducible and transparent as possible with regards to the goal and scope of the study.

Data requirements for this LCA are listed and assessed based on its representativeness (technology coverage, geographic coverage, time coverage), completeness, consistency, reproducibility, transparency and uncertainty in Table 6. Individual data sets are detailed and the data quality assessed in the tables in Appendix A. The overall data quality of this analysis is considered good.

### Table 6. Data Quality Requirements and Assessment.

| Data Quality Requirements | Data Quality Assessment |
|---|---|
| **Time Coverage** | Primary manufacturing data for processes controlled directly by Hydromx, USA were reported for 2018. This data was also used as industry average data for the manufacture of propylene glycol-based HTF, as described in detail in Sections 3.3.1 and 3.6. Secondary data for all HTFs were sourced from the most recent releases of the GaBi Professional and Ecoinvent databases, all released within the past 3 years. Overall the data are very representative of the relevant time period. |
| **Geographic Coverage** | The geographical scope of the manufacturing data for the production of Hydromx, is New York. The manufacturing of all other alternative HTFs is assumed to be in New York to facilitate comparison. Manufacturing energy data is sourced from New York regional grid, while use stage energy is sourced from national grid. See Section 5.3.3 for the results of an analysis on the sensitivity of this LCA to the source of use phase energy. Other materials with few exceptions are based on US production, as is transportation. Overall the geographic coverage is considered very good. |
| **Technology Coverage** | Hydromx and the propylene glycol-based HTF are both manufactured using a simple mixing and packaging process. Data used in the modeling were all derived from processes considered representative of current technology. Secondary data representing the production of locally distributed water required during the installation of the HTFs, are recent and represent currently used technologies. Overall the data are representative of the technology used. |
| **Precision** | Primary data used for this study were measured directly from manufacturing processes. Secondary data were sourced from GaBi LCI databases obtained from Thinkstep. Precision of individual LCI data sets are assessed and reported in Appendix A. Overall precision of data used in this LCI is high |
| **Completeness** | All relevant material input and output flows are modeled for each of the HTFs evaluated in this study. No input or output flows are excluded. Industry accepted values for relative energy consumption during use are well established and were used for propylene glycol and inhibited water. These values were confirmed using published data from existing brand-named products. While a similar value for nano-based HTFs has not yet been established, case studies were used to characterize the relative efficiency of the Hydromx HTF. Overall, all necessary data and values are modeled and thus the completeness of the study is considered good. |
| **Representative ness** | Representativeness of data reflects the degree to which individual data sets reflect the true population of interest. LCI data sets for each HTF are assessed individually for representativeness in Appendix A. While surrogate or proxy chemicals were used for three HTF constituents lacking available LCI data, the overall influence of the use of these surrogate chemicals to the study was demonstrated to be very low. Overall, the representativeness of data used for this study is considered high. |
| **Consistency** | To ensure consistency, assumptions concerning modeling and data selection were applied uniformly across alternatives, where applicable. For example, chemicals common to multiple alternatives (e.g. propylene glycol) were modeled as supplied by the same source. Manufacturing unit processes similar to the manufacture of chemical-based HTFs were modeled using the primary data collected from Hydromx, which was deemed representative of all mixing processes, and so on. Flows common to different HTFs were modeled uniformly and consistently to limit variability on the findings. |
| **Reproducibility** | Internal reproducibility is possible since the data and the models are stored and available in the Gabi modeling software toolkit used by Ecoform. External reproducibility is also possible, informed by the high level of transparency provided throughout the report. Unit process flows are reported for each HTF in Appendix B along with sample calculations for the development of the flows. Key primary (manufacturer specific) and secondary (generic) LCI data sources are summarized in Appendix A. Extensive discussion on assumptions made is also provided in Section 5.4. Modeling diagrams are provided in Appendix F. |
| **Transparency/ Source** | Modeling activity and LCI datasets are transparently disclosed in the project report, including data sources (see Appendices A and B). |
| **Uncertainty** | The majority of the data used in this process are well-defined data sets in well-established public databases. However, surrogate data for a small number of chemicals were used to represent chemicals/materials for which data did not exist. In all cases the contribution of the chemical to the overall composition is small, and therefore the affects of such surrogates are necessarily small. In addition, the use of case studies to quantify the expected energy efficiency of Hydromx introduces an element of uncertainty related to the use of empirical data and small number of samples. While the case study approach has merit and observed results are reasonably grouped, the influence of this data on the overall outcomes of this study is substantial, and thus the overall assessment for uncertainty is medium to high. |

# 4 LIFE-CYCLE IMPACT ASSESSMENT

Impacts to a variety of key environmental and resource categories for the HTFs are presented for each of the evaluated use scenarios. Results reflect impacts associated with the life-cycle product chain consistent with the scope of the inventory data, described in Section 3.

## 4.1 Life-Cycle Inventory and Impact Parameters

Results of the LCA are reported using impact categories specified in the PCR, presented in Table 7. Impact results have been calculated using TRACI 2.1 characterization factors, unless otherwise noted.

**Table 7. Life-Cycle Impact Categories – TRACI 2.1**

| Abbreviation | Parameter | Units |
|---|---|---|
| **AP** | Acidification potential | kg $SO_2$ eq |
| **EP** | Eutrophication potential | kg N eq |
| **GWP** | Global warming potential | kg $CO_2$ eq |
| **ODP** | Depletion of stratospheric ozone layer | kg CFC-11 eq |
| **POCP** | Photochemical ozone creation potential | kg $O_3$ eq |
| **ADP- Fossil** | Abiotic depletion of resources – Fossil fuels | MJ surplus |

Important Note: Results presented in this report are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Life-cycle inventory indicators specified in the PCR are listed in Table 8 for categories related to resource use and waste. These values, calculated and reported by scenario for each HTF, are presented by module in Appendix C.

**Table 8– Life Cycle Inventory Indicators**

| Abbreviation | Parameter | Unit |
|---|---|---|
| **Material Resources** | | |
| $RPR_M$ | Renewable resources used as raw materials | kg |
| $RPR_E$ | Renewable resources used as energy | MJ |
| $NRPR_M$ | Non-renewable resources used as materials | kg |
| $NRPR_E$ | Non-renewable resources used as energy | kg |
| FE | Fossil Energy | MJ |
| BE | Bio Energy[1] | MJ |
| OE | Other Energy | MJ |
| FW | Net use of fresh water | $m^3$ |
| DW | Direct water used by core processes | $m^3$ |
| SM | Secondary resources used as materials | kg |
| RSF | Renewable secondary fuels | MJ, net calorific value |
| RE | Recovered energy | MJ, net calorific value |
| LU | Land Use | Acre |
| **Outflow and Waste Parameters** | | |
| HW | Hazardous waste | kg |
| NHW | Non-hazardous waste | kg |
| RW | Radioactive Waste | kg |
| RGSW | Releases to ground and surface water | $m^3$ |
| RIA | Releases to Indoor Air | kg |
| MR | Materials for recycling | kg |

[1]Energy content of biomass does not include that used for feed or food.

## 4.2 LCA Results

Impacts to a variety of key environmental and resource categories for the HTFs are presented for each of the two use scenarios. In each scenario, the results reflect the impacts associated with the temperature control of 1 square meter of space. Each of the scenarios were constructed from data using real world case studies. Further descriptions of each scenario and the case study data used are presented in Appendix B. Complete life cycle and inventory results are broken out and reported by life-cycle module in Appendix C.

Critical analyses of the comparative results for each scenario are presented in Section 5, including a dominance analysis in Section 5.1, and analyses of the sensitivity of the model to important factors in Section 5.3. It is important to note that LCIA results displayed in this section are relative expressions and do not predict impacts on category endpoints, exceeding of thresholds, safety margins or risks.

### 4.2.1 Residential/Office Building

Heat transfer fluids are often used in systems to control the indoor temperature of occupied buildings. The load on such systems is dependent on various factors, many of which are similar in residential and commercial buildings. Shared factors include occupation of the building for long periods of time, the continuous need to maintain a climate comfortable for occupants, and the potential loss of heating and cooling during the ingress and egress of building occupants and the use of windows. Due to these similarities, both of these building types are represented in a combined scenario based on a typical 200 square meter residential building with an energy usage of 13,500 kWh. Additional details on this scenario are presented in Section 3.3.3 and in Appendix B.

Life-cycle impacts were evaluated for each of the HTFs under this scenario and are presented in Table 9, below. Lifecycle results are broken out by life-cycle stage and by module in Appendix C.

**Table 9. Life Cycle Impacts –Residential/Office**

| LCA Categories | | Hydromx | Inhibited Water | Propylene Glycol |
|---|---|---|---|---|
| **Acidification** | (kg $SO_2$) | 1.69 | 2.21 | 2.45 |
| **Eutrophication** | (kg N eq) | 0.0713 | 0.093 | 0.103 |
| **Global Warming** | (kg $CO_2$) | 600 | 784 | 869 |
| **Ozone Depletion** | (kg CFCs) | 2.01E-10 | -4.20E-11 | 1.46E-10 |
| **Photochem Ozone Creation** | (kg $O_3$ eq) | 14.1 | 18.4 | 20.4 |
| **Abiotic Depletion- Fossil** | (MJ Surplus) | 589 | 766 | 851 |

### 4.2.2 Data Center

Data centers are building spaces dedicated to housing banks of electronic servers. Heat generated by continuous server operation requires cooling systems capable of maintaining strict climate conditions over extended periods of server operation. In this scenario, HTFs were evaluated for a 350 square meter data center space utilizing 160,000 kWh of energy for a baseline inhibited water HTF system. This scenario was constructed using parameters similar to those of the HBO case study presented in the appendices to this report. Additional details on this scenario are presented in Section 3.3.3 and in Appendix B of this report

Life-cycle impacts were evaluated for each of the HTFs under this scenario and are presented in Table 10, below. Lifecycle results are broken out by life-cycle stage and by module in Appendix C.

**Table 10. Life Cycle Impacts – Data Center**

| LCA Categories | | Hydromx | Inhibited Water | Propylene Glycol |
|---|---|---|---|---|
| **Acidification** | (kg $SO_2$) | 11.5 | 15 | 16.6 |
| **Eutrophication** | (kg N eq) | 0.484 | 0.63 | 0.699 |
| **Global Warming** | (kg $CO_2$) | 4,070 | 5,310 | 5,890 |
| **Ozone Depletion** | (kg CFCs) | 2.07E-09 | -2.84E-10 | 1.57E-09 |
| **Photochem Ozone Creation** | (kg $O_3$ eq) | 95.4 | 124 | 138 |
| **Abiotic Depletion- Fossil** | (MJ Surplus) | 4,000 | 5,190 | 5,770 |

# 5 ANALYSIS OF LCA RESULTS

Results of the life-cycle impact assessment demonstrate clearly the environmental impacts associated with each of the HTFs under specific conditions. In each of the scenarios considered, the use of Hydromx appears to offer significant environmental benefits over the other traditional HTFs. Understanding why the relative performance of Hydromx is better requires a deeper analysis into the performance of the system and the drivers of that performance.

## 5.1 Dominance Analysis

In order to gain insight into the environmental impacts reported in Section 4.2, a dominance analysis was performed for the evaluated HTFs to determine what life-cycle stages and flows contribute to the majority of the impacts. While this section focuses on the Residential/Office scenario only, analysis of the Data Center scenario yields similar conclusions. Charts for the Data Center scenario are presented in Appendix E.

### 5.1.1 Hydromx

Using Hydromx as a baseline, Figure 3 presents the contribution of individual life-cycle stages to each of the six evaluated environmental impact categories.

A few conclusions can be drawn directly from the figure. For five of the six categories, it is clear that the impacts result almost entirely from the total energy consumed by the climate control (HVAC) system during the use phase of the life-cycle. For these categories, the use-stage energy accounted for a minimum of 93 percent of the impacts for each category, contributing greater than 99% percent of the impacts in all of the non-ozone depletion categories. This finding is not unexpected given the energy intensive nature of the system during use, and the relative longevity of the product over time.

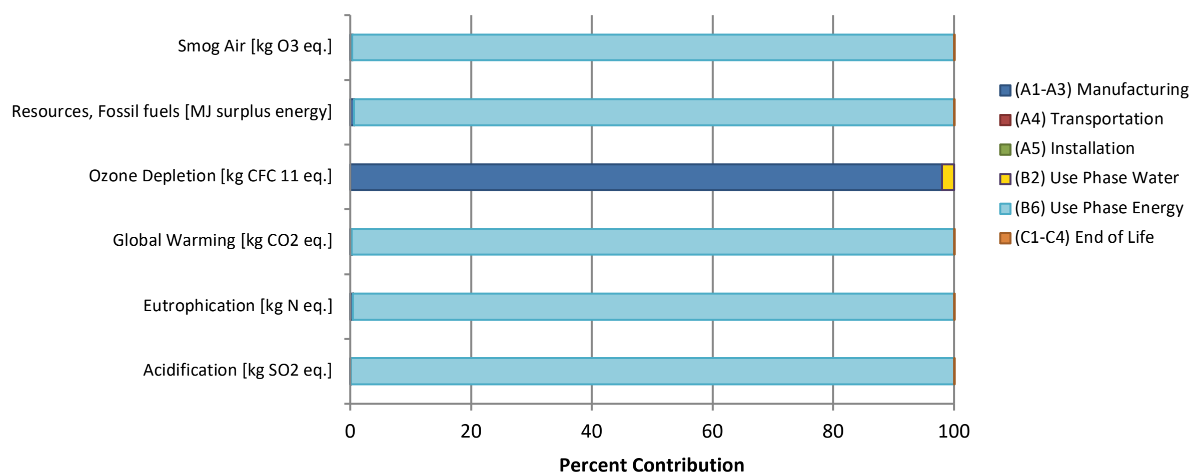



**Figure 3. Hydromx Impacts by LC stage (% contribution) – Residential/Office**

While the heat transfer fluid serves an important function in the efficient operation of the system, it achieves its function passively, without triggering directly the consumption of materials or fuels, thereby limiting their potential influence. Rather, the value of a superior-performing HTF is that it facilitates the more efficient transfer of heat, in effect reducing the time of operation of a system and its associated fuel consumption. The importance of this dynamic to the overall life-cycle cannot be overstated. As shown in Section 5.3, use phase energy consumption becomes dominant after only a few months of operation, and after two years of operation accounts for well over 90% of the impacts in almost every category. It is therefore not surprising to see greater than 99% of the impacts resulting from the use phase for HTFs with a service life that routinely stretches for well over a decade.

The ozone depletion impact category is the lone exception. Unlike the other categories, it is not reliant on the use-stage energy consumption. In fact, use stage energy consumption fails to contribute in any measureable way to ozone depletion, which is measured in chlorofluorocarbon-11 equivalents. Rather, as shown in the figure, ozone depletion is driven primarily from the contributions of the upstream manufacturing stage (A1-A3), and to a lesser extent those from the use-maintenance stage (B2). The contributions of individual flows and processes in these stages are presented in Figure 4, below.

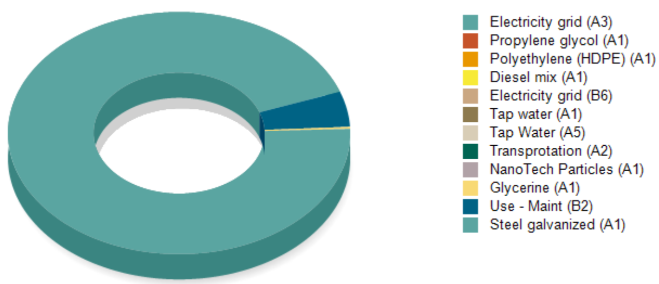



**Figure 4. Hydromx Processes Contributing to Ozone Depletion- Residential/Office**

The most significant contribution to the ozone depletion category is from galvanized steel, which is used to craft the protective cage for the large totes used to transport the product. Galvanized steel from the transport packaging also accounts for the contribution to ozone depletion from the use-maintenance phase, which is accounting for the periodic additions made to the HTF to keep it operating efficiently. The extent to which steel is driving this category is at first surprising given that the totes are used only in transport, and are uniformly reused once emptied. A single cage uses roughly 18 kg of steel for a 945 L (250 gal) tote, as shown in the table in Section 3.3.1. However, it is the case that no other product flows contribute even minimally to the ozone depletion category, making the relatively minor contributions from the steel dominant. To this point, no other flows in the analysis contribute more than 0.1 percent to this category.

### 5.1.2 Traditional HTFs

Results for the traditional HTFs, propylene glycol-based and inhibited water were calculated and charted for analysis. The contributions by inhibited water to select environmental impact categories, reported by life-cycle module, are presented in Figure 5. A second chart for propylene glycol-based HTF is presented in Figure 6.

Much like the analysis for Hydromx, all of the non-ozone depletion categories are dominated by the production of energy consumed during the use phase. Contributions to all categories ranged above 99 percent. The absence of upstream impacts associated with the production of chemicals, manufacturing of product, or transportation to installation site, all of which are not required for an inhibited water collectively work to increase the influence of any use phase impacts. While this is slightly offset by the manufacture of inhibiting agent and increased production of water, it makes little difference in any of the analyses given the relatively small amount of inhibitor, benign nature of water production, and the overall dominance of the consumption of energy over the use phase.

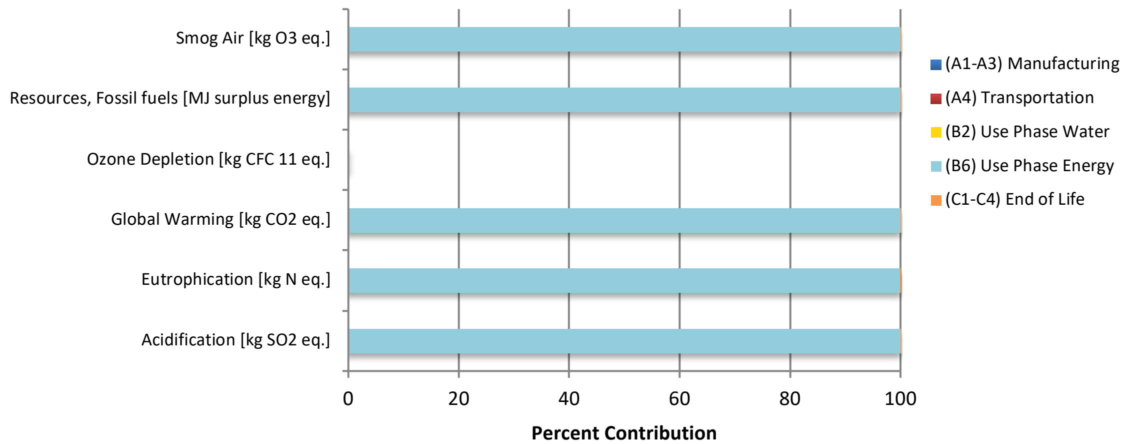



**Figure 5. Water Impacts by LC stage (% contribution) – Residential/Office**

The most striking difference to the Hydromx profile is again in the ozone depletion category. While contributions to ozone depletion for Hydromx were driven almost exclusively by the production of galvanized steel, there are no such requirements for bulk packaging in an inhibited water system, and the production of tap water does not involve any opportunities for chlorofluorocarbon release. In fact, the model exhibited no substantive contribution to ozone depletion, registering an overall net credit to the category.

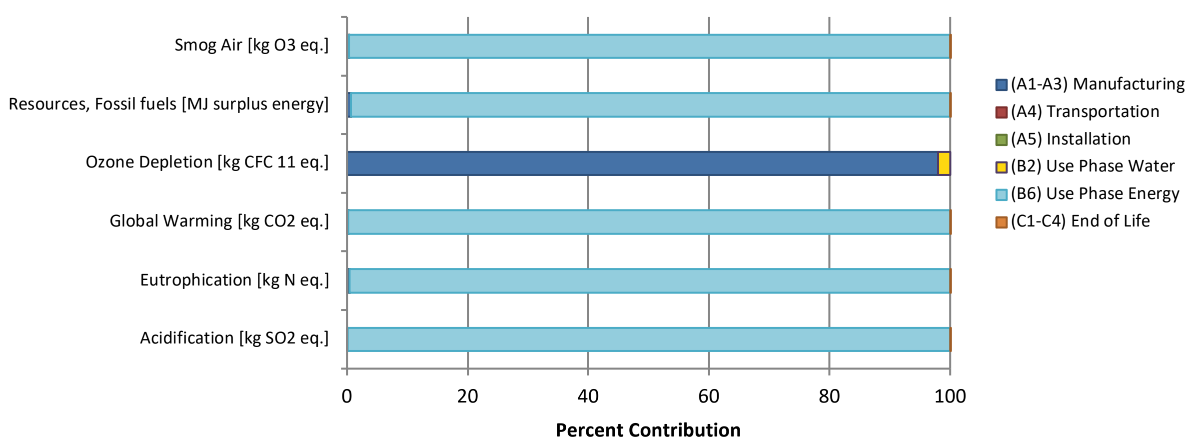



**Figure 6. Glycol/Water Impacts by LC stage (% contribution) – Residential/Office**

A breakdown of contributions to various life-cycle impact categories for a propylene glycol system are presented in Figure 6. The chart is nearly identical to that of the Hydromx alternative. This is in part a result of the parameters used in this modeling exercise. Given the comparative nature of this study, the similarities between the two chemical-based HTFs (e.g. both contain propylene glycol and are concentrates requiring significant dilution), and the availability of primary data for Hydromx, it was assumed that much of the production of propylene glycol-based HTF was done in a manner identical to that of Hydromx. These assumptions were reviewed by industry manufacturers and assessed as credible (e.g. similar manufacturing processes, shipment containers, etc). Given the above, it is expected that any differences in percent contribution between the systems would derive from the influence of unique chemical constituents within the formulations. However, as was seen in the Section 5.1.1, formulation chemicals exerted little noticeable influence on any impacts. As such, the similarities in the two systems in terms of dominance are expected. Further analysis of Figure 6 will yield findings similar to those reported in Section 5.1.1 for Hydromx, identifying similar drivers with only subtle differences in percent contribution.

## 5.2 Comparative Analysis

Understanding of the life-cycle results presented in Section 4.2.1-4.2.2 is enhanced by comparing the results of Hydromx for each scenario directly to those of the other HTF alternatives. Such a comparison is presented in Table 11, below.

**Table 11. Comparative Results of Hydromx vs Other HTFs – Residential/Office**

| LCA Categories | | Residential/Office | | Data Center | |
|---|---|---|---|---|---|
| | | Water | Propylene Glycol | Water | Propylene Glycol |
| **Acidification** | (kg $SO_2$) | 26.7% | 36.7% | 26.4% | 36.3% |
| **Eutrophication** | (kg N eq) | 26.4% | 36.4% | 26.2% | 36.3% |
| **Global Warming** | (kg $CO_2$) | 26.6% | 36.6% | 26.4% | 36.5% |
| **Ozone Depletion** | (kg CFCs) | -306% | -31.7% | -263% | -27.5% |
| **Photochem Ozone Creation** | (kg $O_3$ eq) | 26.5% | 36.5% | 26.1% | 36.5% |
| **Abiotic Depletion- Fossil** | (MJ Surplus) | 26.1% | 36.4% | 25.9% | 36.2% |

The environmental performance of Hydromx compares favorably to that of propylene glycol or inhibited water. When compared to inhibited water, the net benefits of Hydromx are greater than 26 percent for any impact category, while benefits approach 36 percent compared to a propylene glycol-based HTF. This is due to the influence of use phase energy consumption on the overall impacts in a category. This influence continues to grow with the operation of the system over time, eventually accounting for more than 96% of the impacts of any category (see Section 5.1) as the relative influence of other stages become minimized over the 20-year product lifetime.

Over time, the net benefits converge on the use phase energy savings values determined in Appendix B, as these values defined the relative efficiencies of use phase energy consumption of the evaluated HTFs. The rate of convergence of any particular impact category depends on the relative magnitude of the contributions of the other life cycle stages, while the extent of convergence is dependent on the length of the product use phase. This dynamic is independent of the scenario evaluated. The net effect of the HTF's efficiency of heat transfer on overall life-cycle impacts is assessed in a sensitivity analysis in

Section 5.3.2. The rate of convergence for this product system was assessed in a sensitivity analysis of HTF service life, detailed in Section 5.3.2.

It is also noteworthy that the expected results were functionally identical regardless of scenario. It is important to note that the values presented in Table 9 are percent differences between HTF results, and not absolute values. Actual impact results for each HTF, by scenario, are reported in Tables 7 and 8 in Sections 4. While the actual impact values in these tables varied significantly by scenario, the percent differences between values reported for HTFs converged on the values discussed in the previous paragraph. This demonstrates that the key parameters in evaluating the relative environmental benefits of any HTF within a particular system, the key parameters are the efficiency of the heat transfer fluid and the overall energy use of the system. The relative results of this study are unlikely to vary substantially with other factors represented in the scenario (e.g. system volume, area temperature-controlled space).

The lone exception to this trend is in the ozone depletion category. When compared to propylene glycol-based HTFs, the use of Hydromx is virtually identical in terms of impacts, with a small difference of less than 0.5 percent. However, both propylene glycol and Hydromx perform substantially worse than water, with a difference approaching 99 percent. As shown in Figure 5, the model exhibited no substantive contributions to ozone depletion, ensuring that any ozone depleting emissions by other systems would result in higher than normal comparative differences. In fact, the only emissions of CFC-11 in either of the other HTFs are due to a component of the packaging that is almost uniformly reused. As a result, while the water based system is clearly preferable with regard to ozone depletion, the 200+ percent increase in ozone depletion potential shown in Table 9 is much more to do with the near lack of releases from the water system, than any sizeable release resulting from the manufacture of either of the chemical-based HTFs.

When taken in total, the use of the nano-technology based Hydromx results in a significant environmental advantage over the other heat transfer options, regardless of scenario. The magnitude of the net benefits is likely to be directly influenced by the overall magnitude of the energy consumption during the use phase.

## 5.3 Sensitivity Analyses

Due to the dominance of the use phase in the assessment of life cycle impacts of these HTFs, a number of sensitivity analyses were conducted to better understand the influence of key parameters. Specifically, analyses were conducted on the affects of the key HTF parameters of service life, source of energy production, and percent efficiency of heat transfer by the HTF. These analyses are reported and discussed in further detail in this Section.

### 5.3.1 Heat Transfer % Efficiency

The relative efficiency of Hydromx compared to other traditional HTFs was established through a series of case studies presented in Appendix B. These case studies typically involved measuring the performance of Hydromx in real world applications where the performance (i.e. energy consumption) of the system using a traditional HTF has been established and can serve as a baseline. After Hydromx is substituted into the system, the performance over time is directly measured, and the relative efficiency of Hydromx to the baseline can be calculated. This creates a snapshot of the performance of Hydromx, under the specific conditions of the trial.

While the use of case studies is perhaps the best way of directly assessing the performance of Hydromx, under a variety of real world conditions, when combined with other case studies, the collective results create a range of expected performance. As shown in Appendix B, energy savings values reported by the case studies ranged from 21.1% - 33.5%. For this study, the range of values were averaged to calculate an average expected efficiency for Hydromx relative to inhibited water of 26.8%, which then served as the basis of the life-cycle calculations reported in Section 4.

However, given the dominance of use stage energy consumption in the overall life-cycle impacts (see Sections 5.2 and 5.3.2), it is appropriate to explore the affect on system life cycle impacts that would result from the use of an efficiency value (expressed as % energy savings) at either boundary of the reported range of values. As such, the life cycle analysis was recalculated for the residential/office scenario using Hydromx efficiencies (relative to water) of 20% and 34%, values that reflect the entire range of observed performance in the case studies. Selection of these values reflected the most liberal and conservative outcomes of reported case studies. Calculated life-cycle impact results using each of these values are reported in Table 12 below.

**Table 12. Effect of Energy Efficiency on Life Cycle Impacts – Hydromx Residential/Office**

| LCA Categories | | Percent Efficiency | | |
|---|---|---|---|---|
| | | **20%** | **26.8%*** | **34%** |
| **Acidification** | (kg $SO_2$) | 1.77 | **1.69** | 1.57 |
| **Eutrophication** | (kg N eq) | 0.0749 | **0.0712** | 0.662 |
| **Global Warming** | (kg $CO_2$) | 631 | **600** | 558 |
| **Ozone Depletion** | (kg CFCs) | 1.98E-10 | **2.00-10** | 2.02E-10 |
| **Photochem Ozone Creation** | (kg $O_3$ eq) | 14.8 | **14.1** | 13.1 |
| **Abiotic Depletion- Fossil** | (MJ Surplus) | 619 | **589** | 547 |

* Baseline Hydromx efficiency expressed in terms of %energy saved. See Section 4 for results using this value.

Life cycle results reported in Table 12 were used to assess the comparative life cycle impacts of Hydromx versus the other traditional HTFs. Results of the assessment are presented in Table 13.

**Table 13. Comparative Life Cycle Impacts by Energy Efficiency – Hydromx**

| LCA Categories | | Hydromx – 20% | | Hydromx- 34% | |
|---|---|---|---|---|---|
| | | **Inhibited Water** | **Propylene Glycol** | **Inhibited Water** | **Propylene Glycol** |
| **Acidification** | (kg $SO_2$) | 19.6% | 29.8% | 33.9% | 43.8% |
| **Eutrophication** | (kg N eq) | 19.4% | 29.5% | 33.8% | 43.5% |
| **Global Warming** | (kg $CO_2$) | 19.5% | 29.7% | 33.8% | 43.6% |
| **Ozone Depletion** | (kg CFCs) | -306% | -31.7% | -306% | -31.7% |
| **Photochem Ozone Creation** | (kg $O_3$ eq) | 19.4% | 29.7% | 33.7% | 43.7% |
| **Abiotic Depletion- Fossil** | (MJ Surplus) | 19.1% | 29.6% | 33.6% | 43.6% |

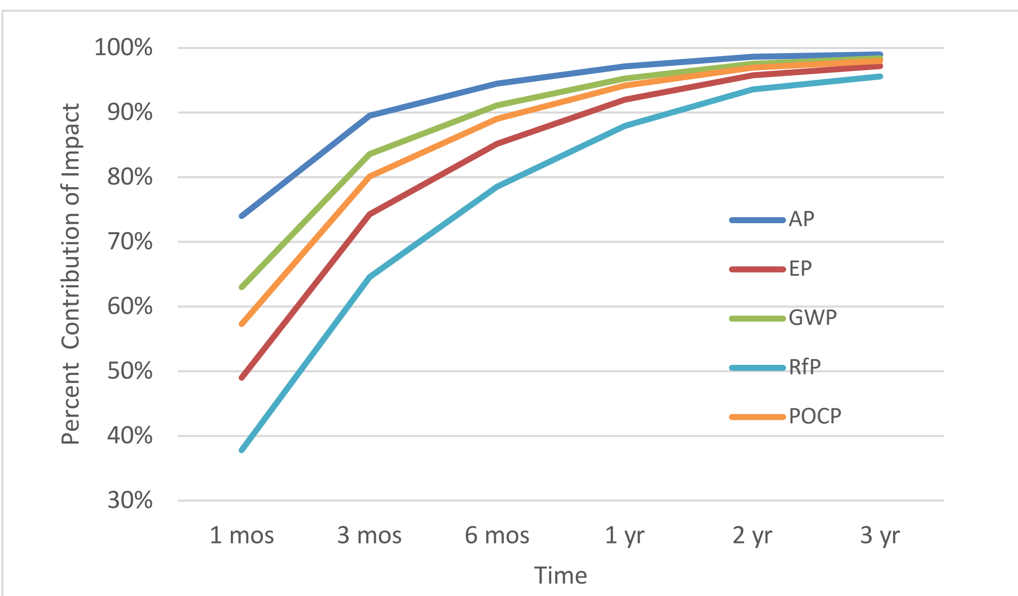
As demonstrated in the table, the results behaved as expected. Energy consumption during the use phase continued to be as dominant at the lower efficiency value of 20% as they were at the original baseline value, approaching the relative energy transfer efficiency of the HTFs. This effect was also observed at the higher value of 34%. Given the analysis in Section 5.2.2 on the affects of service life, it can be concluded that this will be the dominant dynamic for HTFs with a product service life of greater than 3 years. In summary, using the most conservative value observed in the case studies for residential/office scenarios of 20%, the use of Hydromx will result in a minimum benefit to the environment of 19% or greater in every impact category (ozone depletion excluded).

### 5.3.2 HTF Service Life

The expected service life of the HTF is 20 years for all of the HTFs in this evaluation. This extended service life is due, in part, to the closed nature of the systems in which HTFs operate, and to the ability to perform periodic rebalancing of fluid compositions that forestall the need to replace a fluid that has fallen out of balance. However, the lengthy service life the HTFs also accentuates the impacts associated with the use stage, resulting in use stage contributions of greater than 95% of the overall system impacts in nearly every impact category for every HTF evaluated.

Given the direct correlation of service life to use stage energy consumption, an evaluation of the affect of service life on the overall lifecycle impacts was conducted. Using the residential/office scenario for Hydromx as an example, a plot of the percent contribution of the use phase over time is presented in Figure 7, below.

**Figure 7: Use stage contribution to Impacts over time - Hydromx**




While the time axis is not to linear scale, the figure does clearly depict the increasing influence of the use stage over the first three years of operation. It is clear from the figure that it does not take long for the energy consumption to begin to dominate, diminishing the influence of the other product life-cycle stages within the first few months of operation. At six months of operation, use stage impacts accounted for a minimum of 78% of all impact categories, ranging as high as 94% of the total acidification impacts for the entire life-cycle. After one year, the use stage has accounted for a minimum of 88% of all impacts in any category and by three years the use stage is accounting for fully 95% or more of the overall system impacts in all categories shown. These values exceed 99% of impacts in a category by the 20-year service life of the HTF. This explains the results in Table 13 from Section 5.2. As the contributions of the use stage become dominant, the overall comparative life-cycle impacts approach the energy efficiency values calculated from the case studies, as the influence of other processes and materials in the product life cycle fades in the overall analysis.

A couple of important conclusions can be made relative to the product service life from this analysis. First, the selection of a term of service life for an HTF is the most influential factor in the overall impacts for the product life cycle. The figure above demonstrates that after 3 months of operation, the period of operation accounts for 65-90% of the impacts for any particular category, and that any service life of 2 years or more will be driven almost exclusively by the impacts associated with the production of the energy consumed during the use phase. This emphasizes and underscores the importance of the energy transfer efficiency of the HTF to the results of this study.

However, this analysis also demonstrates that the overall term of the service life is not critical to the comparative results of the study shown in Section 5.2. After only 2 years of operation, any differences in the content, manufacturing, transportation, or disposal of the HTFs account for less than 5% of the overall impacts, a value not significant when compared with the energy efficiency differences between the HTFs. As such, while the overall magnitude of the impacts would certainly vary according to service life, the relative differences between the HTFs will not. This same conclusion would hold for most other factors in the life cycle, such as manufacturing energy or proxies for materials that might vary by reasonable amounts (e.g. up to 50%).

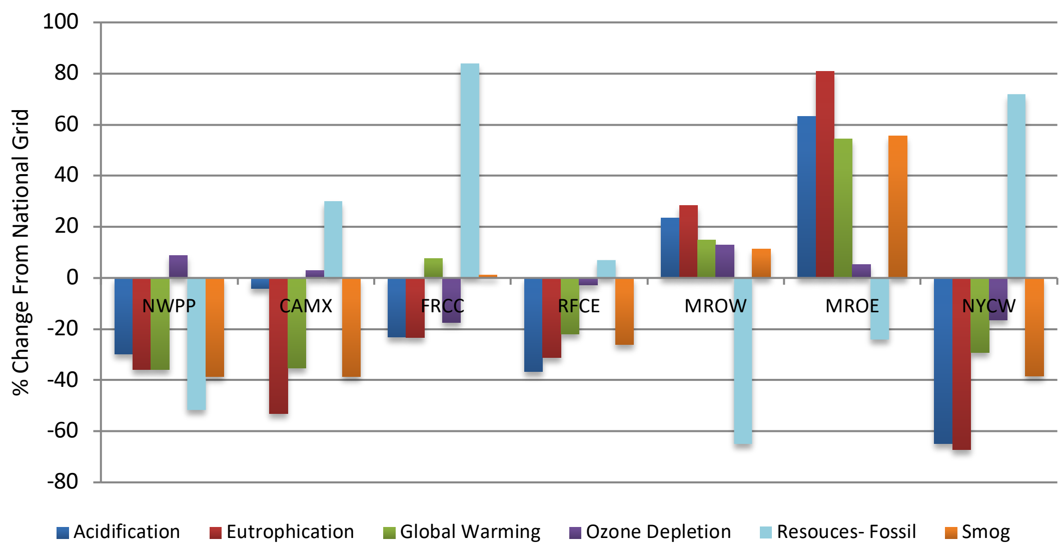
It is also noteworthy that this dynamic is likely not affected by the conditions of the scenario selected. While changes in factors such as system volume and floor area have a direct impact on the balance of contributions to the life cycle (i.e., a smaller area with a larger system volume would emphasize the material content of the system relative to the baseline), given the dominance of the use phase in the scenarios evaluated, the changes would need to be dramatic and unrealistic to have a meaningful affect on the conclusions of the study. To confirm this, a range of scenario conditions were evaluated using case study data (ie. Floor space/system volume profiles) with results modifying the curve shown in Figure 7 by only a year or two for the most extreme selections. Given the expected service life of 20 years, the variation in scenario conditions is not a likely to be meaningful to study conclusions

### 5.3.3 Source of Energy

The generation of the energy consumed results in environmental impacts, the nature and quantity of which depends directly on the manner of energy generation. Results presented in this LCA were developed using energy sourced from the national grid, a power grid developed from the average of the US regional energy grids. However, the power generation profiles for regional grids can vary significantly from region-to-region both in the manner of generation, and the overall percentage of energy sourced. For example, while the regional grid for Florida (FRCC) relies heavily on energy generated from natural gas (67%), the pacific northwest region (NWPP) derives much of its energy from hydroelectric sources (47%), while the energy grid from parts of Wisconsin (MROE) relies primarily on coal-derived energy sources (65%). Each of these methods of production generate environmental Impacts specific to the nature and source of the energy, and thus the impacts per unit of power generated from each grid can vary substantially from one another.

To better understand the significance of the selection of the national grid as the source of energy, a sensitivity analysis was performed using hydromx. The analyses recalculated the life cycle results of this study substituting a different regional power grid for each run. All told, seven regional power grids were assessed, chosen primarily for their variation in power profiles. The results of this analysis for Hydromx using the residential/office scenario are presented in Figure 8.

**Figure 8. Affect of Energy Grid Selection for Use Phase Consumption on Life Cycle Impacts - Hydromx Residential/Office Scenario**

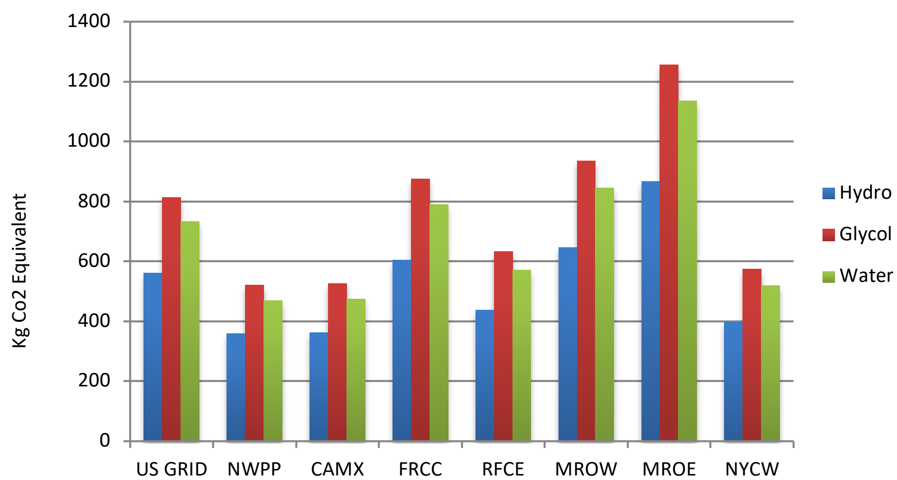



Lifecycle impacts calculated using the each of the seven regional grids are plotted In the above figure as a percent change from the baseline LCA results reported in Section 4. Those impacts stretching below the baseline reflect a decrease in that impact category from the baseline, while those stretching upward reflect an increase in impacts. The longer the bar, the greater the difference. The baseline impacts were developed using the national grid energy profile. Energy grid power profiles developed for the US EPA e-Grid Program for the year 2016 were used for this analysis. ([https://www.epa.gov/energy/power-profiler#/](https://www.epa.gov/energy/power-profiler#/))

As can be seen from the figure, the impact results can vary significantly within any one impact category based on the location of the installation and the resulting power grid. Using the global warming category as an example, the change in impacts can range from as much as 35% less to as much as 55% greater than those associated with energy produced from the national grid, depending on the location. This is a significant variation in impacts across the different regions. The affect of location on the expected LCA results for other impact categories is similar in scale for most of the all other categories, except ozone depletion, which has a much lower variance (due to the minimal correlation of energy generation on ozone depletion). Further analysis as to the drivers of this variation provides us little insight into the performance of HTFs, as nearly all of the impacts (+95%) result from the production of energy, with the cumulative contributions of the remaining product life cycle of little consequence. For further analysis on the comparision of energy generation grids using LCA, please refer to one of the many studies that are available. One such study was conducted by the World energy Council. (https://www.worldenergy.org/assets/downloads/PUB_Comparison_of_Energy_Systens_using_lifecycle_2004_WEC.pdf)

While Figure 8 quantifies the affect that geographic location might have on the overall results, it does little to demonstrate any substantive differences in environmental impacts between the HTFs arise from the regional grid. In figure 9, the global warming impacts expressed in kg of CO2 equivalents for eash of the HTfFs were calculated using each of the seven regional grids, and plotted side-by-side to facilitate comparison. Again, the values reflect those for the residential/office scenario.

**Figure 9. Global Warming Potential Impacts by Regional Grid – Residential/Office**




As expected, the magnitude of the global warming impacts for an HTF varied substantially across he various energy grids, increasing or decreasing relative to the national grid by the range defined in Figure 8. However, the relative % difference between the HTFs for any one grid remained fairly constant, varying by less than a percentage point across grids. This is expected, primarily due to the relatively little influence of factors other than energy consumption during use phase to the overall impacts of the study (less than 2%). Given the dominance of energy consumption over the 20 year service life, the relative differences between the HTFs mathematically approaches the difference in the calculated energy transfer efficiencies of the system. For additional information on this dynamic, please refer to the analysis presented in Section 5.2, Service Life.

## 5.4 Assumptions

A number of assumptions were made in this study. Important assumptions include:

- Formulation for propylene glycol-based HTF is assumed to be 40/60 propylene glycol and water, mixed on-site, which is typical practice in the field. A phosphate-based inhibitor was also considered. Proprietary mixtures of propylene glycol-based HTFs (e.g. RTU versions) may contain additional additives, which are not considered in this comparison. The exclusion of such additives from this study is a conservative assumption that potentially underestimates the overall impacts of the propylene glycol-based HTF.

- The formulations for the propylene glycol-based and inhibited water HTFs are typical of those used widely within the industry. They were derived from publicly available information on the describing the composition of actual products and the use of professional judgment. They are viable formulations, and as such are considered representative for their HTF types.
- Production data for the propylene glycol-based alternative were assumed to be identical to that of Hydromx, as both HTFs are manufactured in batch form using similar unit processes.
- Propylene glycol was considered to be supplied by the identical source as that of Hydromx. Since this study was not evaluating a particular propylene glycol product, and because propylene glycol is an ingredient of Hydromx, this assumption was deemed appropriate to limit variability.
- Water for the baseline water alternative was drawn directly from that tap, as is typical in water-based HTF applications. As such, no transportation of the water was considered. Water was also assumed to have a phosphate inhibitor to prevent corrosion, which is a commonly used inhibitor. Although there are several types of inhibitors available, the inhibitor was assumed to be potassium phosphate due to its applicability to the HTF and the availability of life cycle inventory data.
- Make up rates for all HTFs were assumed to be 0.1% of the composition per year. In the field, make-up rates can vary on several factors, mostly related to system losses through maintenance (e.g. leaks, etc), or chemical rebalancing. The value used is typical. Given the dominance of the use phase, this assumption is likely not determinative.

Additional assumptions as they apply to the study may be found in individual sections of this report.

## 5.5 Limitations and Uncertainties

With any LCA, there are a number of limitations and uncertainties that should be considered as appropriate context for the study. One such limitation was the manner in which the glycol/water alternative was characterized. Formulation of the glycol portion of the HTF was assumed to be pure propylene glycol, based on established knowledge. While this is often typical, additives are sometimes added in small quantities to improve the overall performance of the final mixture after dilution. These additives can vary from product to product and are not publicly disclosed. The overall effect of the presence for these additives on the results of this analysis is unknown, but because of the small percentages involved, it is not expected to be significant.

As an emerging technology, there is not yet a clear and widespread understanding of the mechanisms and overall performance factors for Hydromx or other nano technology-based HTFs. The complicated nature of the heat transfer system and the various external factors that influence the overall performance of the system make isolating and evaluating the performance of the HTF difficult. As such, a series of case studies with a variety of factors were utilized to assess a range of possible outcomes. These case studies involved actual installations where the performance of the existing HTF was quantified and used as a baseline before replacing the HTF with Hydromx and measuring the subsequent performance. The hydromx data were then compared to the performance of the baseline HTF and the efficiency (measured as % energy saved) calculated. Cumulative results of the case studies were then used to inform the life-cycle analyses. While the case study approach has merit, controlling the variability of other factors while collecting real world data, there are a limited but growing number of studies from which to draw conclusions and an absence of widely accepted test data. Given the influence of use phase energy consumption in the overall life cycle impacts, this approach is a limitation.

The absence of primary manufacturing data for the propylene glycol-based alternative is a potential uncertainty. Propylene glycol-based HTFs are manufactured using a process similar to the mixing and packaging process used to manufacture Hydromx. To limit variability, it was assumed that the manufacturing process for a propylene glycol-based HTF was identical to that of Hydromx. Based on professional knowledge of HTF manufacturing, this assumption is likely representative of the actual manufacturing process, and thus is unlikely to introduce significant error to the study.

Some of the formulations contained chemicals for which no life-cycle inventory data exist. In such cases, chemicals were either modeled by using combinations of data sets that together mimic the synthesis process for the missing chemical, by using available data for a chemically or structurally similar chemical, or as a last resort by determining an average inventory profile from other chemicals that serve an identical function (e.g. non-ionic surfactants). Given that any such approach involves an approximation in lieu of actual inventory data for the specific chemical, the affect of this uncertainty on the overall results of this analysis can not be specifically determined, but is unlikely to be significant given the relative impacts of any of the chemicals involved.

Finally, secondary data sources were used in this analysis in lieu of data that could not be collected directly. Secondary data sources can vary significantly in quality and completeness and it is not often easy to determine the quality of a data set. Every effort was made by the authors to vet any secondary data sources for quality and completeness, but the authors cannot ultimately guarantee the accuracy of this data. For data sets that had a profound affect on the overall results of this study, such as those for energy and water production, alternative analyses were performed using substitute data sets to confirm the integrity of the results.

# 6 ADDITIONAL ENVIRONMENTAL INFORMATION

No additional environmental information is claimed or reported in this study

# 7 REFERENCES

[1] Bare, J., TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 2011, Vol 13/5, p. 687.

[2] International EPD Program, *PCR for Heat Transfer Fluids for Heating and Cooling, 2017*. Available at *https://www.environdec.com/PCR/Detail/?Pcr=11291*

[3] ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures.

[4] ISO 14040:2006 Environmental management - Life cycle assessment – Principles and framework.

[5] ISO 14044:2006 Environmental management - Life cycle assessment – Requirements and guidelines.

[6] ISO 21930:2007 Sustainability in building construction – Environmental declaration of building products.

[7] NSF International, Addendum to Environdec Heat Transfer Fluid PCR – North America, Version 1.2. 2019

# APPENDIX A – LIFE CYCLE INVENTORY DATASETS

Life cycle inventory datasets used in the models of HTFs are presented in Table A1, along with key characteristics of each set. HTFs utilizing each set are identified, and data are evaluated for precision, representativeness and uncertainty according to ISO 14044. See Section 3.7 for an overall assessment of data quality.

### Table A1. Life Cycle Inventory Data Sets – All HTFs

| Dataset | HTF | Source/ Time | Geography | Precision | Representativeness/ Uncertainty |
|---|---|---|---|---|---|
| Propylene Glycol (via PO Hydrogenation) | H, P | GaBi DB, (2018) | US | Excellent | Excellent |
| Tap water | H, P, W | GaBi DB, (2018) | EU | Excellent | Good, incorrect geography |
| Electricity grid mix | H, P, W | GaBi DB, (2018) | US | Good | Excellent |
| Electricity grid mix, NYUP | H | GaBi DB, (2018) | New York | Good | Excellent |
| HTF Mixing | H, P | Hydromx (2018) | US | Excellent | Excellent |
| Glycerine, at plant | H | GaBi DB, (2018) | RNA | Excellent | Good, incorrect geography |
| Diesel mix at filling station | H, P, W | GaBi DB, (2018) | US | Excellent | Excellent |
| Carbon Black (proxy for nano tech) | H | GaBi DB, (2018) | Ger | Low | Fair (high uncertainty) |
| Potassium Phosphate (modeled proxy for Inhibitor) | P, W | Modeled | US | Good | Fair (high uncertainty) |
| Potassium Phosphate (Proxy for Sodium Molybdate) | H | Modeled | US | Good | Fair (high uncertainty) |
| Truck – TL/Dry Van (EPA SmartWay) | H, P, W | GaBi DB, (2018) | US | Excellent | Excellent |
| Steel hot dip, galvanized | H, P | ILCD (2017) | Glo | Excellent | Good, incorrect geography |
| Polyethylene High Density Granulate (HDPE/PE) | H, P | GaBi DB, (2018) | EU | Excellent | Good, incorrect geography |
| Water deionized (reverse-osmosis/electro-deionization) | H, P, W | GaBi DB, (2018) | US | Good | Excellent |
| Hazardous waste in waste incineration plant | H, P | GaBi DB, (2018) | US | Good | Good |
| Plastics wastes in waste incineration plant | W | GaBi DB, (2018) | US | Good | Excellent |
| Municipal waste water treatment | W | GaBi DB, (2018) | US | Good | Excellent |

## APPENDIX B – CASE STUDIES AND USE SCENARIOS

In order to evaluate the relative life cycle benefits of Hydromx as compared to traditional HTFs, two scenarios were developed and assessed:

- Data Center
- Residential/Office

Each scenario represents unique conditions under which HTF-based systems are employed. Residential/Office scenarios represent the climate control of a space largely populated by humans, characterized by human activity such as entering and leaving a space, maintaining temperature comfortable to occupants, and operating for extended periods of time relative to use. The data center scenario is uniquely different, characterized by the need for tight, climate control over a non-stop, continuous period of time, and are characterized by the generation of heat by banks of electronic servers. Data centers are also not likely affected by loads to the interior climate brought on by such things as open windows or doors.

The efficiency with which a HTF is able to transfer heat is a critical factor in the performance of the fluid. For traditional HTFs like water and propylene glycol-based fluids, the relative performance of these fluids is well understood within the industry. For example, a system using propylene glycol is less efficient than the same system using water, with the extent of the de-rate depending on the concentration of the propylene glycol mixture and the temperature extremes expected in the ambient environment. For this study, the use of a 40% propylene glycol-based HTF is expected to consume 10% more energy as compared to water, under the identical conditions.

However, for innovative fluids new to the market – such as Hydromx—consensus values have not yet been established. Simply measuring these values is difficult. There are a number of factors that can influence the effectiveness of a system. Hours of operation, the system design, and the difference in temperature between the system and the surrounding environment are just a few of the many factors that can make it difficult to isolate the overall effectiveness. To control for these variables in any one instance would require that a single system be operated under the same conditions using different fluids, and measurements taken. Such a case study would isolate the variables and allow for informed assessment of the effect of the fluid on the overall energy efficiency of the system. A series of such comparisons over a category of use conditions would further strengthen the knowledge gained.

To assess the heat transfer efficiency of Hydromx, a series of case studies were performed and the energy savings relative the baseline fluid reported. These case studies were each developed with the cooperation of early adopters and are based on the actual data measured both during their operation using traditional HTFs, and then after installing Hydromx. When taken together, the results collectively reflect the expected energy savings associated with the use of Hydromx, relative to water, over a variety of conditions. Case studies were grouped relevant to the two scenarios and presented in Tables B1 and B2. Reports related to each case study have been cited and are publicly available either online or by request. Calculations for the values in the Table are embedded at the bottom of each table.

## Table B1. Hydromx Case Studies - Residential/Office

| Case Study[a,b] | Building Usage | Building Use Area (m2) [A] | Vol of system (L) [B] | Baseline Energy (kWh) [C] | Energy w Hydromx (kWh) [D] | Energy saved % [E] |
|---|---|---|---|---|---|---|
| Forest Green Rovers, UK | Leisure | 2,900 (31,200 ft$^2$) | 1,200 (317 gal) | 226,064 | 165,541 | 26.8 |
| Nottingham Trent University, UK | Dwelling | 1800 (32,300ft$^2$) | 880 (232 gal) | 305 kwh/HDD[c] | 224 kWh/HDD | 26.6 |
| SL Green, New York | Office | 8,450 (91,000 ft$^2$) | 13,250 (3,500 gal) | 1,758,000 | 1,371,000 | 22 |
| Hamworthy Heating, UK | Office | 975 (10,500ft$^2$) | 900 (237 gal) | 66.94 kWh/HDD[c] | 46.29 kWh/HDD | 30.9 |
| Hotel Lalit, India[d] | Dwelling | NA | 40,000 | 67.5 (L H2O/L HSD) | 100.8 (L H2O/L HSD) | 33.2 |
| Sawai Man Singh, India | Heath care | -- | 470 (125 gal) | 14.28 Kwh/hr | 10.42 Kwh/hr | 27 |
| BUPA Global, UK | Dwelling | 1,550 (16,700 ft$^2$) | 800 (211 Gal) | 470,700 | 371,400 | 21.1 |
| (E.g. Calculations) | (--) | (--) | (--) | (measured) | (measured) | (C-D/C)*100 |

[a] Hydromx Case Studies. Accessed on-line September 9, 2019. https://www.hydromx.com/hydromx-case-studies/

[b] All case studies can be obtained directly by request to info@hydromx.com

[c] Heating Degree Days (HDD), a method recommended by the Carbon Trust and Building Institute for assessing the energy consumption of heat transfer systems. https://www.carbontrust.com/media/137002/ctg075-degree-days-for-energy-management.pdf

[d] Hotel lalit case study involved energy associated with production of hot water. Energy efficiency was expressed in terms of liters of hot water production per liter of High Speed Diesel consumed, with the more efficient system producing more water per unit of fuel. Although case study not focused specifically on heating of space, it is still relevant to establishing the efficiency of the heat transfer relative to water in a heat transfer system.

## Table B2. Hydromx/Water Case Studies – Data Center

| Case Study | Building Usage | Building Use Area (m2) [A] | Vol of system (L) [B] | Base Glycol Energy (kWh) [C] | Energy w Hydromx (kWh) [D] | Energy saved % [E] |
|---|---|---|---|---|---|---|
| Home Box Office (HBO)[a] , NY | Data Center | 300 (3,200 ft$^2$) | 2,544 (670 gal) | 185,700[b] | 120,700 | 27.8 |
| Cass County Electric Co-Op, Fargo ND | Data Center | (--) | (--) | [measured in 5 min increments] | [measured in 5 min increments] | 22[c] |
| (E.g. Calculations) | (--) | (--) | (--) | (adj to water) | (measured) | $(C_{adj}-D/C_{adj})$*100 |

[a] HBO Case study. Accessed on-line September 9, 2019. https://www.hydromx.com/hydromx-case-studies/

[b]Baseline energy consumption was based on glycol-based mixture, which was adjusted to a water equivalent using the efficiency value for glycol (given as 0.9 in Table B3) prior to the calculation of the energy saved. (185,700 * 0.9 =167,100 kWh). This was necessary to establish a efficiency value for hydromx which is calculated relative to water (i.e. water is 1)

[c] Energy consumption was measured relative to a propylene glycol baseline in a continuous side-by-side trial and savings reported directly in case study on monthly basis. The ability of Hydromx to allow free cooling at extreme temps resulted in elevated energy savings in the highest 3 months (nov – jan), and thus these months were excluded from this calculation (i.e only Aug- Oct are included). The average % energy savings were then adjusted to a water baseline and the % savings to that water baseline was then determined.

In Table B1, the percent energy savings is reported for each case study reflecting the expected savings over the baseline fluid due to the use of Hydromx. The reported percent energy savings range from 21% to a high of 31%, with an average energy savings of 26.8% for Hydromx, when compared to water. This value reflects the typical energy savings that can be expected when using Hydromx as the HTF across the wide variety of conditions evaluated.

Using the case studies reported in Table B2 and the method described above, an expected energy savings for Hydromx of 24.9% was determined for data centers. The expected energy consumption values of HTFs relative to water are presented in Table B3 for each scenario. The values reflect the energy savings/losses typically associated with the use of that HTF, relative to an identical water-based system. Reports related to each of the case studies reported in this document, as well as case studies for other uses of Hydromx are available on the Hydromx USA website.

**Table B3. Expected Energy Consumption of HTFs (Relative to Water)**

| Parameter | Life-Cycle Evaluation Scenarios | |
|---|---|---|
| | Residential/ Office | Data Center |
| **Heat Transfer Efficiency Ratio** | | |
| – Hydromx[a] | -26.8% | -24.9% |
| – Propylene Glycol[b] | +10% | +10% |
| – Water | - | - |

[a] Value based on Average of Energy saved (%) of relevant Case studies. See Tables B1-B2 for case studies. Case study values were averaged to reflect the typical performance of the HTF relative to water over a variety of system and use conditions. The expected energy consumption is calculated relative to water using percent difference math equation to achieve the average energy saved (%) determined from case studies. $|V1-V2| / [(V1+V2)/2] * 100 = \%$ diff.

[b] De-rate (i.e. capacity factor) for propylene glycol is due to the higher specific gravity of propylene relative to water and the decreased flow rate. Together these reduce the amount of heat a liter of glycol/water can carry relative to a liter of water. Derate is based on concentration of prop glycol and temperature. For a 40% mixture of glycol, this value is 0.91 at 45 F, resulting in 10% more energy consumption. Source: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=2ahUKEwjumtWXnZzlAhWRFzQIHeSFBEAQFjABegQICBAC&url=https%3A%2F%2Faeroventic.com%2Fattachment%2Fdownload%2F1421&usg=AOvVaw3UEeXXYLxamADiOiqrmrwi

Residential/Office Scenario

The unit process flows for the Residential/Office scenario are presented in Table B4, and report the flows per 1 $m^2$ of temperature-controlled space as required by the PCR. Material content reflects the entirety of the HTF as used, meaning that no materials were excluded. Energy consumption values for the use stage energy reflect the cumulative energy consumed per functional unit over the 20 year RSL.

**Table B4. Unit Process Flows per 1 m$^2$ Temperature- Controlled Space (kg) – Residential/Office**

| | Hydromx | Propylene Glycol | Water |
|---|---|---|---|
| **Materials**[a] | | | |
| Water | | | |
| - Concentrate/product[b] | 0.135 | - | 0.678 |
| - Dilution | 0.349 | 0.424 | - |
| Propylene glycol | 0.194 | 0.291 | - |
| Glycerine | 0.022 | - | - |
| Sodium molybdate | 0.004 | - | - |
| Triazole | 0.004 | - | - |
| Potassium Phosphate | - | 0.012 | 0.021 |
| Nano additives | 0.037 | - | - |
| Packaging | | | |
| - HDPE | 0.0138 | 0.0106 | 0.00034 |
| - Galvanized Steel | 0.0069 | 0.0070 | - |
| **Total Mass (gross)** | 0.766 | 0.746 | 0.699 |
| **Energy** | | | |
| - Manufacturing (kWh) | 0.000338 | 0.00033 | NA[c] |
| - Use Stage (kWh) – 20 yrs | 1,031 | 1,493 | 1,350 |

[a] Includes make-up materials at 0.1 percent per year over RSL.
[b] Because water is the HTF for Inhibited water, production of the water is modeled in module A3 and thus reported as in product and not as dilution.
[c] Water from local system is used. Mfg energy for water production is embedded in secondary data set.

Data Center Scenario

The unit process flows for the Data Center scenario are presented in Table B5, and report the flows per 1 m$^2$ of temperature-controlled space as required by the PCR. Material content reflects the entirety of the HTF as used, meaning that no materials were excluded. Energy consumption values for the use stage energy reflect the cumulative energy consumed per functional unit over the 20 year RSL.

**Table B5. Unit Process Flows per 1 m$^2$ Temperature- Controlled Space (kg) – Data Center**

| | Hydromx | Propylene Glycol | Water |
|---|---|---|---|
| **Materials**[a] | | | |
| Water | | | |
| - Concentrate/product[b] | 1.34 | - | 6.64 |
| - Dilution | 3.4 | 4.16 | - |
| Propylene glycol | 1.9 | 2.85 | - |
| Glycerine | 0.219 | - | - |
| Sodium molybdate | 0.037 | - | - |
| Triazole | 0.037 | - | - |
| Potassium Phosphate | - | 0.121 | 0.202 |
| Nano additives | 0.365 | - | - |
| Packaging | | | |
| - HDPE | 0.135 | 0.103 | 0.0034 |
| - Galvanized Steel | 0.067 | 0.069 | - |
| **Total Mass (gross)** | 7.51 | 7.30 | 6.84 |

| | | | |
|---|---|---|---|
| **Energy** | | | |
| - Manufacturing (kWh) | 0.000338 | 0.000323 | NA[c] |
| - Use Stage (kWh) – 20 yrs | 6,980 | 10,100 | 9,140 |

[a] Includes make-up additions at 0.1 percent per year over RSL.
[b] Because water is the HTF for Inhibited water, production of the water is modeled in module A3 and thus reported as in product and not as dilution.
[c] Water from local system is used. Mfg energy for water production is embedded in secondary data set.

Calculations for Inputs

Process flows were calculated per functional unit of 1 m2 of temperature-controlled space for each HTF using the approach shown below. In Tables B6 and B7. Examples based on the residential scenario and the ingredient polyethylene glycol in the Hydromx formulation are given in gray within the tables.

**Table B6. Residential Scenario – Given Values**

| Temp Controlled Area (m2) [A] | Volume System (l) [B] | Dilution Rate (%) [C] | Density - Water (kg/l) [D] | Density – Hydro Conc (kg/l) [E] | Density – Hydro Dilute (kg/l) [F] |
|---|---|---|---|---|---|
| 200 | 140 | 50% | 0.998 | 1.129 | 1.066 |
| (Table 4) | (Table 4) | (App E) | | (App E) | (App E) |

**Table B7. Residential Scenario Example – Calculated Values**

| Mass Conc System (kg) [G] | Mass H2O System (kg) [H] | HTF Mass in System (kg) [I] | Mass HTF Fcn Unit (kg/m2) [J] | PG in Conc (%) [K] | Mass PG (conc) Fcn Unit (kg/m2) [L] |
|---|---|---|---|---|---|
| 79.0 | 69.9 | 148.9 | 0.746 | 26% | 0.194 |
| (B*C*E) | (B*C*D) | (G+H) | (B*F/A) | (Table 1) | (J*K/A) |

# APPENDIX C – LCA RESULTS

### Table C1. Propylene Glycol Results by Module – Residential/Office

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 3.59E+00 | 4.31E-02 | 1.08E-04 | 0.00E+00 | 7.17E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.48E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.80E-04 | MND |
| **AP [kg $SO_2$ eq]** | 1.98E-03 | 1.26E-04 | 2.10E-07 | 0.00E+00 | 3.96E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.45E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.05E-06 | MND |
| **EP [kg N eq]** | 2.51E-04 | 1.01E-05 | 8.86E-08 | 0.00E+00 | 5.02E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.03E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.23E-05 | MND |
| **GWP [kg $CO_2$ eq]** | 1.36E+00 | 2.18E-02 | 1.81E-04 | 0.00E+00 | 2.73E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.67E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.89E-04 | MND |
| **ODP [kg CFC 11 eq]** | 1.89E-10 | -1.23E-16 | -2.56E-18 | 0.00E+00 | 3.78E-12 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -4.64E-11 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.71E-17 | MND |
| **POCP [kg $O_3$ eq]** | 4.12E-02 | 2.96E-03 | 4.05E-06 | 0.00E+00 | 8.24E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.03E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.84E-05 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.79E+01 | 3.24E-01 | 1.01E-03 | 0.00E+00 | 5.58E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.40E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.22E-03 | MND |
| **$RPR_E$ (MJ)** | 2.79E+01 | 3.24E-01 | 1.01E-03 | 0.00E+00 | 5.58E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.40E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.22E-03 | MND |
| **$NRPR_M$ (kg)** | 2.19E+00 | 1.00E-02 | 5.50E-05 | 0.00E+00 | 4.39E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.91E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.76E-04 | MND |
| **$NRPR_E$ (kg)** | 2.19E+00 | 1.00E-02 | 5.50E-05 | 0.00E+00 | 4.39E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.91E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.76E-04 | MND |
| **FE (MJ)** | 2.19E+00 | 1.00E-02 | 5.50E-05 | 0.00E+00 | 4.39E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.91E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.76E-04 | MND |
| **BE (MJ)** | 5.49E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.38E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.24E-24 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.01E-23 | MND |
| **OE (MJ)** | 2.79E+01 | 3.24E-01 | 1.01E-03 | 0.00E+00 | 5.58E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.40E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.22E-03 | MND |
| **FW (m3)** | 5.34E-03 | 3.88E-05 | 4.25E-04 | 0.00E+00 | 1.07E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.89E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -7.31E-04 | MND |
| **DW (m3)** | 0.00E+00 | 0.00E+00 | 4.24E-04 | 0.00E+00 | 8.48E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 2.45E-08 | 2.63E-09 | 1.71E-12 | 0.00E+00 | 4.90E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.13E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.34E-12 | MND |
| **NHW (kg)** | 2.18E-02 | 1.22E-05 | 5.60E-05 | 0.00E+00 | 4.36E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.39E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.26E-04 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RGSW (m3)** | 2.32E-01 | 1.20E-02 | 1.62E-05 | 0.00E+00 | 4.64E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.12E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.47E-04 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 1.58E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 2.07E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

## Table C2. Hydromx Results by Module – Residential/Office

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 3.95E+00 | 5.62E-02 | 8.90E-05 | 0.00E+00 | 7.91E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.85E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.97E-04 | MND |
| **AP [kg $SO_2$ eq]** | 2.30E-03 | 1.64E-04 | 1.73E-07 | 0.00E+00 | 4.61E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.69E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.18E-06 | MND |
| **EP [kg N eq]** | 2.82E-04 | 1.31E-05 | 7.29E-08 | 0.00E+00 | 5.64E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.10E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.26E-05 | MND |
| **GWP [kg $CO_2$ eq]** | 1.44E+00 | 2.83E-02 | 1.49E-04 | 0.00E+00 | 2.87E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.98E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.01E-03 | MND |
| **ODP [kg CFC 11 eq]** | 2.28E-10 | -1.60E-16 | -2.11E-18 | 0.00E+00 | 4.57E-12 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.20E-11 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.81E-17 | MND |
| **POCP [kg $O_3$ eq]** | 3.97E-02 | 3.86E-03 | 3.34E-06 | 0.00E+00 | 7.94E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.40E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.89E-05 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.14E+00 | 1.31E-02 | 4.53E-05 | 0.00E+00 | 4.29E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.32E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.94E-04 | MND |
| **$RPR_E$ (MJ)** | 2.14E+00 | 1.31E-02 | 4.53E-05 | 0.00E+00 | 4.29E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.32E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.94E-04 | MND |
| **$NRPR_M$ (kg)** | 3.07E+01 | 4.22E-01 | 8.30E-04 | 0.00E+00 | 6.13E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.63E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.41E-03 | MND |
| **$NRPR_E$ (kg)** | 3.07E+01 | 4.22E-01 | 8.30E-04 | 0.00E+00 | 6.13E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.63E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.41E-03 | MND |
| **FE (MJ)** | 3.07E+01 | 4.22E-01 | 8.30E-04 | 0.00E+00 | 6.13E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.63E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.41E-03 | MND |
| **BE (MJ)** | 6.89E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.38E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.24E-24 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.01E-23 | MND |
| **OE (MJ)** | 2.14E+00 | 1.31E-02 | 4.53E-05 | 0.00E+00 | 4.29E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.32E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.94E-04 | MND |
| **FW (m#)** | 5.79E-03 | 5.06E-05 | 3.50E-04 | 0.00E+00 | 1.16E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.37E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -7.50E-04 | MND |
| **DW (m3)** | 1.35E-04 | 0.00E+00 | 3.49E-04 | 0.00E+00 | 6.98E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 2.33E-08 | 3.42E-09 | 1.41E-12 | 0.00E+00 | 4.67E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.23E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.56E-12 | MND |
| **NHW (kg)** | 2.02E-02 | 1.59E-05 | 4.61E-05 | 0.00E+00 | 4.04E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.03E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.48E-04 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RGSW (m3)** | 2.47E-01 | 1.57E-02 | 1.33E-05 | 0.00E+00 | 4.95E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.46E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.71E-04 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 2.07E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 2.07E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

## Table C3. Water Results by module – Residential/Office

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 2.65E-02 | 2.98E-03 | 0.00E+00 | 0.00E+00 | 1.59E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.66E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.47E-04 | MND |
| **AP [kg $SO_2$ eq]** | 1.52E-05 | 8.70E-06 | 0.00E+00 | 0.00E+00 | 9.10E-09 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.21E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.81E-06 | MND |
| **EP [kg N eq]** | 1.29E-06 | 6.97E-07 | 0.00E+00 | 0.00E+00 | 7.75E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.30E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.17E-05 | MND |
| **GWP [kg $CO_2$ eq]** | 1.43E-02 | 1.50E-03 | 0.00E+00 | 0.00E+00 | 8.54E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.84E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.42E-04 | MND |
| **ODP [kg CFC 11 eq]** | -2.02E-15 | -8.48E-18 | 0.00E+00 | 0.00E+00 | -1.21E-18 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -4.20E-11 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.53E-17 | MND |
| **POCP [kg $O_3$ eq]** | 2.87E-04 | 2.04E-04 | 0.00E+00 | 0.00E+00 | 1.72E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.84E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.75E-05 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.09E-02 | 6.92E-04 | 0.00E+00 | 0.00E+00 | 1.25E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.73E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.44E-04 | MND |
| **$RPR_E$ (MJ)** | 2.09E-02 | 6.92E-04 | 0.00E+00 | 0.00E+00 | 1.25E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.73E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.44E-04 | MND |
| **$NRPR_M$ (kg)** | 2.23E-01 | 2.24E-02 | 0.00E+00 | 0.00E+00 | 1.33E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.26E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.87E-03 | MND |
| **$NRPR_E$ (kg)** | 2.23E-01 | 2.24E-02 | 0.00E+00 | 0.00E+00 | 1.33E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.26E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.87E-03 | MND |
| **FE (MJ)** | 2.23E-01 | 2.24E-02 | 0.00E+00 | 0.00E+00 | 1.33E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.26E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.87E-03 | MND |
| **BE (MJ)** | 2.05E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.32E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.28E-24 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.71E-23 | MND |
| **OE (MJ)** | 2.09E-02 | 6.92E-04 | 0.00E+00 | 0.00E+00 | 1.25E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.73E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.44E-04 | MND |
| **FW (m#)** | 7.06E-04 | 2.68E-06 | 0.00E+00 | 0.00E+00 | 4.23E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.42E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -6.96E-04 | MND |
| **DW (m3)** | 6.78E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.35E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 1.80E-10 | 1.81E-10 | 0.00E+00 | 0.00E+00 | 1.08E-13 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.54E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.94E-12 | MND |
| **NHW (kg)** | 1.49E-04 | 8.43E-07 | 0.00E+00 | 0.00E+00 | 8.91E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.97E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.87E-04 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSW (m3)** | 1.05E-03 | 8.30E-04 | 0.00E+00 | 0.00E+00 | 6.28E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.91E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.02E-04 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 3.40E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 3.40E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

## Table C4. Propylene Glycol Results by Module – Data Center

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 3.50E+01 | 4.21E-01 | 1.06E-03 | 0.00E+00 | 6.96E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.74E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.66E-03 | MND |
| **AP [kg $SO_2$ eq]** | 1.93E-02 | 1.23E-03 | 2.06E-06 | 0.00E+00 | 3.84E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.66E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.95E-05 | MND |
| **EP [kg N eq]** | 2.45E-03 | 9.86E-05 | 8.69E-07 | 0.00E+00 | 4.87E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.96E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.20E-04 | MND |
| **GWP [kg $CO_2$ eq]** | 1.33E+01 | 2.13E-01 | 1.78E-03 | 0.00E+00 | 2.64E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.87E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.69E-03 | MND |
| **ODP [kg CFC 11 eq]** | 1.85E-09 | -1.20E-15 | -2.51E-17 | 0.00E+00 | 3.67E-11 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.14E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.63E-16 | MND |
| **POCP [kg $O_3$ eq]** | 4.03E-01 | 2.89E-02 | 3.98E-05 | 0.00E+00 | 8.00E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.38E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.80E-04 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.14E+01 | 9.79E-02 | 5.40E-04 | 0.00E+00 | 4.26E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.29E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.62E-03 | MND |
| **$RPR_E$ (MJ)** | 2.14E+01 | 9.79E-02 | 5.40E-04 | 0.00E+00 | 4.26E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.29E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.62E-03 | MND |
| **$NRPR_M$ (kg)** | 2.73E+02 | 3.16E+00 | 9.90E-03 | 0.00E+00 | 5.42E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.45E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.07E-02 | MND |
| **$NRPR_E$ (kg)** | 2.73E+02 | 3.16E+00 | 9.90E-03 | 0.00E+00 | 5.42E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.45E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.07E-02 | MND |
| **FE (MJ)** | 2.73E+02 | 3.16E+00 | 9.90E-03 | 0.00E+00 | 5.42E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.45E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.07E-02 | MND |
| **BE (MJ)** | 2.05E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.32E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.28E-24 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.71E-23 | MND |
| **OE (MJ)** | 2.14E+01 | 9.79E-02 | 5.40E-04 | 0.00E+00 | 4.26E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.29E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.62E-03 | MND |
| **FW (m#)** | 5.21E-02 | 3.80E-04 | 4.17E-03 | 0.00E+00 | 1.04E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.31E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -7.16E-03 | MND |
| **DW (m3)** | 0.00E+00 | 0.00E+00 | 4.16E-03 | 0.00E+00 | 8.32E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 2.39E-07 | 2.57E-08 | 1.68E-11 | 0.00E+00 | 4.76E-09 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.15E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.17E-11 | MND |
| **NHW (kg)** | 2.13E-01 | 1.19E-04 | 5.49E-04 | 0.00E+00 | 4.23E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.97E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.09E-03 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RGSW (m3)** | 2.27E+00 | 1.17E-01 | 1.59E-04 | 0.00E+00 | 4.50E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.43E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.27E-03 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 1.55E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 1.55E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

## Table C5. Hydromx Results by Module – Data Center

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 3.87E+01 | 5.50E-01 | 8.72E-04 | 0.00E+00 | 7.75E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.96E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.83E-03 | MND |
| **AP [kg $SO_2$ eq]** | 2.26E-02 | 1.61E-03 | 1.70E-06 | 0.00E+00 | 4.51E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.14E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.08E-05 | MND |
| **EP [kg N eq]** | 2.76E-03 | 1.29E-04 | 7.15E-07 | 0.00E+00 | 5.53E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.81E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.24E-04 | MND |
| **GWP [kg $CO_2$ eq]** | 1.41E+01 | 2.78E-01 | 1.46E-03 | 0.00E+00 | 2.81E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.06E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.94E-03 | MND |
| **ODP [kg CFC 11 eq]** | 2.23E-09 | -1.57E-15 | -2.07E-17 | 0.00E+00 | 4.47E-11 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -2.17E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.73E-16 | MND |
| **POCP [kg $O_3$ eq]** | 3.89E-01 | 3.78E-02 | 3.27E-05 | 0.00E+00 | 7.78E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.50E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.85E-04 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.10E+01 | 1.28E-01 | 4.44E-04 | 0.00E+00 | 4.20E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.93E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.80E-03 | MND |
| **$RPR_E$ (MJ)** | 2.10E+01 | 1.28E-01 | 4.44E-04 | 0.00E+00 | 4.20E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.93E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.80E-03 | MND |
| **$NRPR_M$ (kg)** | 3.01E+02 | 4.13E+00 | 8.14E-03 | 0.00E+00 | 6.01E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.53E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.26E-02 | MND |
| **$NRPR_E$ (kg)** | 3.01E+02 | 4.13E+00 | 8.14E-03 | 0.00E+00 | 6.01E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.53E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.26E-02 | MND |
| **FE (MJ)** | 3.01E+02 | 4.13E+00 | 8.14E-03 | 0.00E+00 | 6.01E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.53E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.26E-02 | MND |
| **BE (MJ)** | 6.75E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.35E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.21E-23 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.93E-22 | MND |
| **OE (MJ)** | 2.10E+01 | 1.28E-01 | 4.44E-04 | 0.00E+00 | 4.20E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.93E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.80E-03 | MND |
| **FW (m3)** | 5.68E-02 | 4.96E-04 | 3.43E-03 | 0.00E+00 | 1.14E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.29E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -7.35E-03 | MND |
| **DW (m3)** | 1.35E-04 | 0.00E+00 | 3.49E-04 | 0.00E+00 | 6.98E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 2.29E-07 | 3.35E-08 | 1.38E-11 | 0.00E+00 | 4.57E-09 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.86E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.39E-11 | MND |
| **NHW (kg)** | 1.98E-01 | 1.56E-04 | 4.52E-04 | 0.00E+00 | 3.96E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.05E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.31E-03 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RGSW (m3)** | 2.42E+00 | 1.53E-01 | 1.30E-04 | 0.00E+00 | 4.85E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.90E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.52E-03 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 2.02E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 2.02E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

## Table C6. Water Results by Module – Data Center

| Impact Category | A1-A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LCIA Indicators** | | | | | | | | | | | | | | | |
| **ADP-fossil [MJ]** | 2.59E-01 | 2.91E-02 | 0.00E+00 | 0.00E+00 | 1.55E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.19E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.34E-03 | MND |
| **AP [kg $SO_2$ eq]** | 1.48E-04 | 8.49E-05 | 0.00E+00 | 0.00E+00 | 8.90E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.50E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.71E-05 | MND |
| **EP [kg N eq]** | 1.27E-05 | 6.80E-06 | 0.00E+00 | 0.00E+00 | 7.58E-09 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.30E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.15E-04 | MND |
| **GWP [kg $CO_2$ eq]** | 1.39E-01 | 1.47E-02 | 0.00E+00 | 0.00E+00 | 8.35E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.31E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 9.23E-03 | MND |
| **ODP [kg CFC 11 eq]** | -1.98E-14 | -8.28E-17 | 0.00E+00 | 0.00E+00 | -1.19E-17 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -2.84E-10 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -3.46E-16 | MND |
| **POCP [kg $O_3$ eq]** | 2.80E-03 | 2.00E-03 | 0.00E+00 | 0.00E+00 | 1.68E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.24E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.72E-04 | MND |
| **LCI Metrics** | | | | | | | | | | | | | | | |
| **$RPR_M$ (kg)** | 2.04E-01 | 6.76E-03 | 0.00E+00 | 0.00E+00 | 1.22E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.17E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.31E-03 | MND |
| **$RPR_E$ (MJ)** | 2.04E-01 | 6.76E-03 | 0.00E+00 | 0.00E+00 | 1.22E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.17E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.31E-03 | MND |
| **$NRPR_M$ (kg)** | 2.18E+00 | 2.18E-01 | 0.00E+00 | 0.00E+00 | 1.31E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.55E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.74E-02 | MND |
| **$NRPR_E$ (kg)** | 2.18E+00 | 2.18E-01 | 0.00E+00 | 0.00E+00 | 1.31E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.55E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.74E-02 | MND |
| **FE (MJ)** | 2.18E+00 | 2.18E-01 | 0.00E+00 | 0.00E+00 | 1.31E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.55E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.74E-02 | MND |
| **BE (MJ)** | 7.82E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.83E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.20E-24 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.22E-23 | MND |
| **OE (MJ)** | 2.04E-01 | 6.76E-03 | 0.00E+00 | 0.00E+00 | 1.22E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.17E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.31E-03 | MND |
| **FW (m3)** | 6.91E-03 | 2.62E-05 | 0.00E+00 | 0.00E+00 | 4.14E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.99E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | -6.83E-03 | MND |
| **DW (m3)** | 6.67E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.33E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **SM (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RSF (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RE (MJ)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **LU (acre)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **HW (kg)** | 1.76E-09 | 1.77E-09 | 0.00E+00 | 0.00E+00 | 1.05E-12 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.75E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.78E-11 | MND |
| **NHW (kg)** | 1.46E-03 | 8.23E-06 | 0.00E+00 | 0.00E+00 | 8.72E-07 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.69E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 7.71E-03 | MND |
| **RW (kg)** | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **RGSW (m3)** | 1.02E-02 | 8.10E-03 | 0.00E+00 | 0.00E+00 | 6.15E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.30E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.83E-03 | MND |
| **RIA (kg)** | 0.00E+00 | 0.00E+00 | 3.40E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |
| **MR (kg)** | 0.00E+00 | 0.00E+00 | 3.40E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | MND |

# APPENDIX D – DOMINANCE ANALYSIS SUPPLEMENTAL DATA

Dominance analysis information specific to the Data Center scenario is presented here in Appendix D. This information is supplemental to the information and analysis given in Section 5.2. Similar to the results shown for the Residential/Office scenario, energy consumption during the use phase is the dominant driver of impacts across HTF alternatives. Figure D1, presents the results for Hydromx, while Figure D2 presents result for inhibited water.

Please note, the results for propylene glycol are virtually indistinguishable in these figures from those of Hydromx, and as such have not been replicated her to save space. Differences in % contribution in any impact category between Hydromx and propylene glycol are in the range of 0-0.3%, and are thus indistinguishable in the charts below.

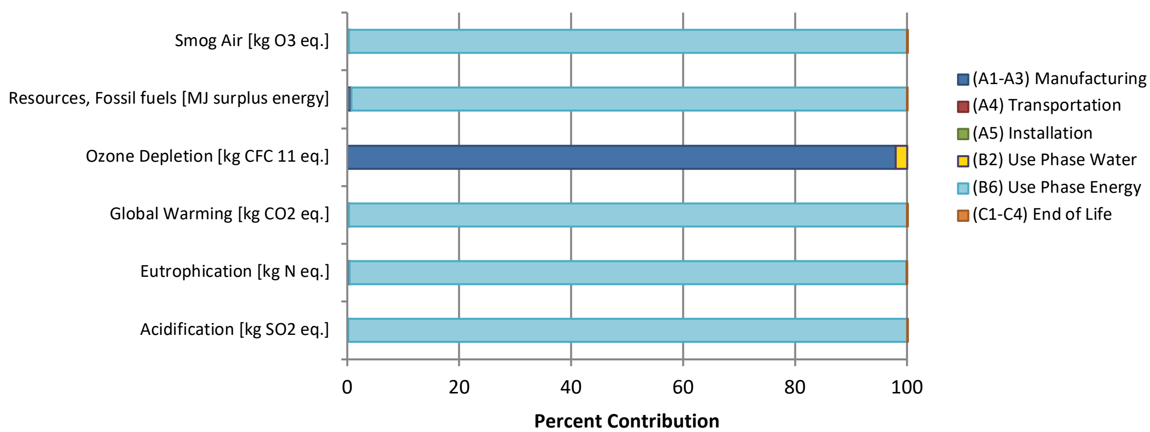



**Figure D1. Hydromx Impacts by LC stage (% contribution) – Data Center**

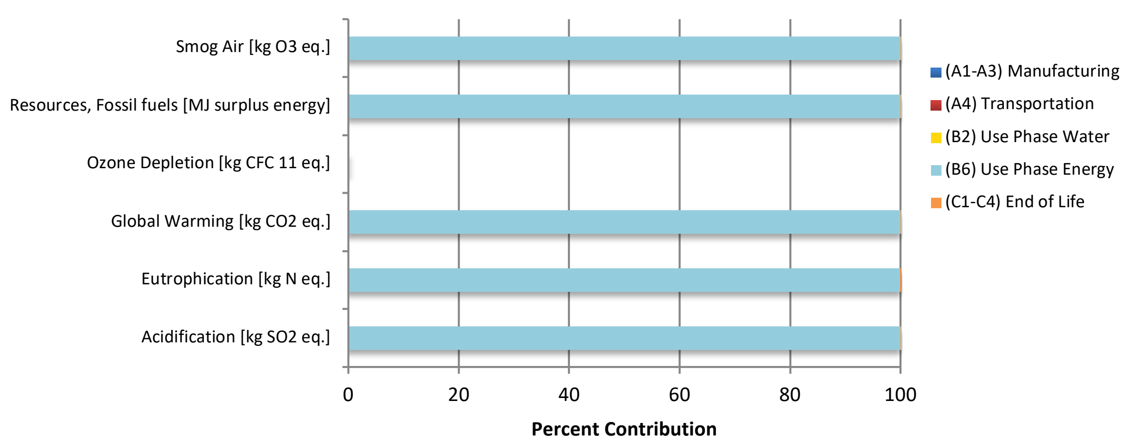



**Figure D2. Inhibited Water Impacts by LC stage (% contribution) – Data Center**

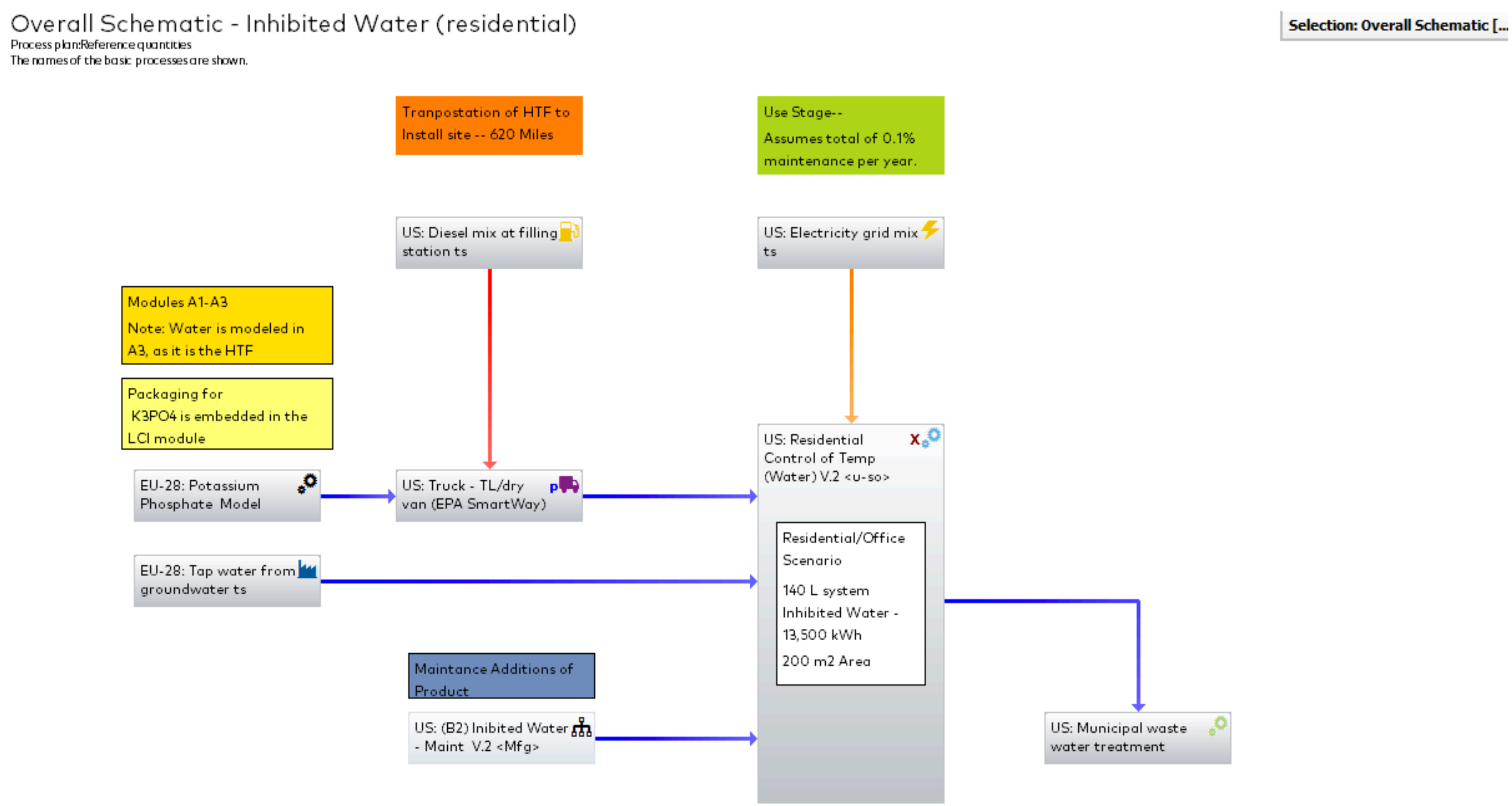
## APPENDIX E – HYDROMX SPECIFICATIONS

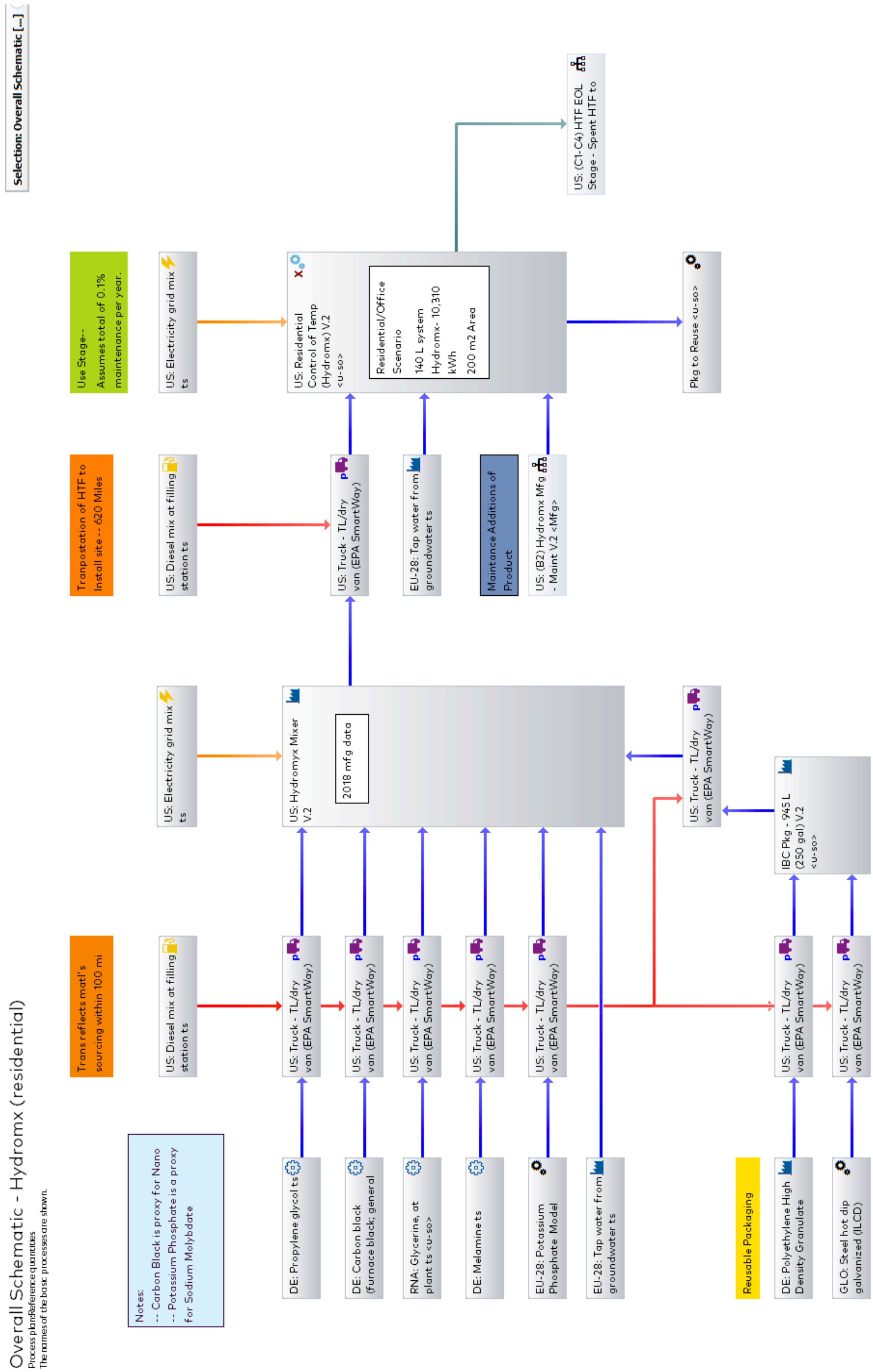
Hydromx is a nano-technology based fluid suitable for heat transfer applications. An extended list of technical specifications for Hydromx is presented in Table D1, below. For more information visit www.hydromx.com.

**Table D1. Hydromx Technical Data**

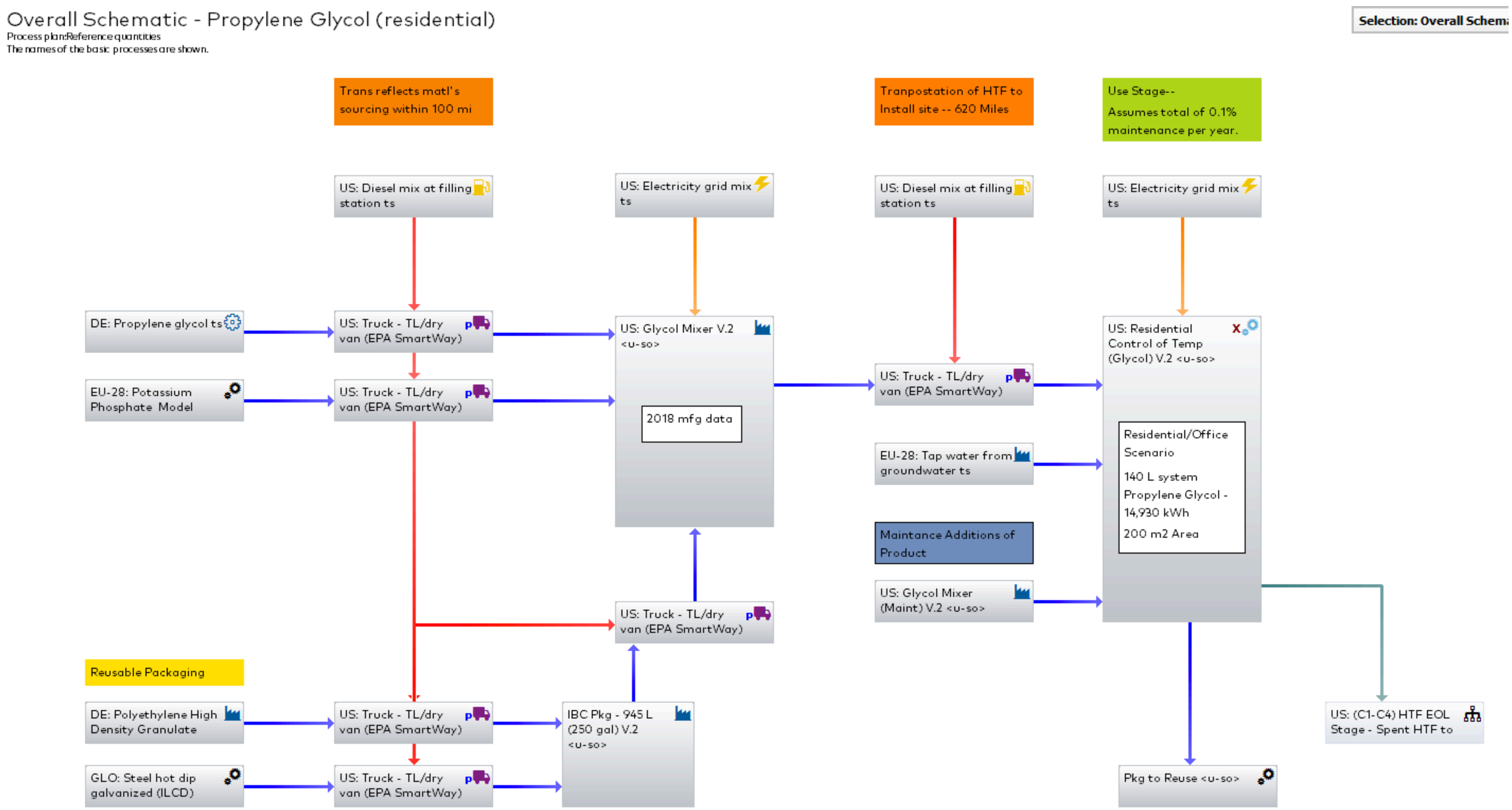
| TECHNICAL SPECIFICATIONS | Measurement Method | Hydromx | Hydromx (as Used) |
|---|---|---|---|
| **Colour (at 20°C)** | ASTM D 1500 | Blue | Blue |
| **Odour (at 20°C)** | - | Intrinsic | Intrinsic |
| **pH (at 20°C)** | ASTM D 1287 | 8.20 – 8.80 | 8.20 – 8.80 |
| **Concentration (at 20°C)** | Refractometric measurement | - | 1.36 |
| **Total Suspended Solid (TSS)** | TS 9546 EN 12880 | < 0.1 | |
| **Dissolved oxygen (mg/lt)** | SM-4500 OG | | 8.46 |
| **Humidity Weight** | TS 9546 EN 12880 | | 100% |
| **Freezing Point** | Potential differences reading by multimeter, under application of liquid nitrogen | - 73°C | -47°C |
| **Boiling Point** | Heating in atmospheric conditions and, temperature measurement by thermocouple | 200°C | 120°C |
| **Vapour Pressure (at 25°C)** | ASTM D6378 (at 25°C) | | DVPE: 2.9 kPa<br>ASVP: 3.8 kPa |
| **Vapour Pressure (at 50°C)** | ASTM D6378 (at 50°C) | | DVPE: 8.3 kPa<br>ASVP: 9.6 kPa |
| **Vapour Pressure (at 80°C)** | ASTM D6378 (at 80°C) | RVPE: 6.7 kPa<br>ASVP: 10.1 kPa | RVPE: 36.4 kPa<br>ASVP: 39.0 kPa |
| **Density (g/cm$^3$)** | Pyknometer (at 25°C) | 1.122 | 1.065 |
| **Electrical Conductivity (City Water 401(µS))** | Conductometer (Hanna Branded) (at 25°C) | 90 | 570 |
| **Total Fe (ppm) (City Water: 0,069)** | Atomic Absorption Spectrometer | 0.169 | 0.0565 |
| **Dynamic Viscosity (cP) (at 20°C)** | Malvern Bohlin Gemini II Rotational Rheometer | 25 | 7.2 |
| **Kinematic Viscosity (cP) (at 20°C)** | Dynamic viscosity divided by density | 22.3 | 6.76 |

## APPENDIX F – GABI MODELS


Overall Schematic - Inhibited Water (residential)
Process plan:Reference quantities
The names of the basic processes are shown.
Selection: Overall Schematic [...
Tranpostation of HTF to Install site -- 620 Miles
Use Stage-- Assumes total of 0.1% maintenance per year.
US: Diesel mix at filling station ts
US: Electricity grid mix ts
Modules A1-A3 Note: Water is modeled in A3, as it is the HTF
Packaging for K3PO4 is embedded in the LCI module
EU-28: Potassium Phosphate Model
US: Truck - TL/dry van (EPA SmartWay)
US: Residential Control of Temp (Water) V.2 <u-so>
Residential/Office Scenario
140 L system
Inhibited Water - 13,500 kWh
200 m2 Area
EU-28: Tap water from groundwater ts
Maintance Additions of Product
US: (B2) Inibited Water - Maint V.2 <Mfg>
US: Municipal waste water treatment



Selection: Overall Schematic [...]
Overall Schematic - Hydromx (residential)
Process plans Reference quantities
The names of the basic processes are shown.
Notes:
-- Carbon Black is proxy for Nano
-- Potassium Phosphate is a proxy for Sodium Molybdate
Trans reflects matl's sourcing within 100 mi
US: Diesel mix at filling station ts
US: Truck - TL/dry van (EPA SmartWay)
DE: Propylene glycol ts
DE: Carbon black (furnace black; general
RNA: Glycerine, at plant ts <u-so>
DE: Melamine ts
EU-28: Potassium Phosphate Model
EU-28: Tap water from groundwater ts
Reusable Packaging
DE: Polyethylene High Density Granulate
GLO: Steel hot dip galvanized (ILCD)
IBC Pkg - 945 L (250 gal) V.2 <u-so>
US: Electricity grid mix ts
US: Hydromyx Mixer V.2
2018 mfg data
Tranpostation of HTF to Install site -- 620 Miles
Maintance Additions of Product
US: (B2) Hydromx Mfg - Maint V.2 <Mfg>
Use Stage-- Assumes total of 0.1% maintenance per year.
US: Residential Control of Temp (Hydromx) V.2 <u-so>
Residential/Office Scenario
140 L system
Hydromx- 10,310 kWh
200 m2 Area
Pkg to Reuse <u-so>
US: (C1-C4) HTF EOL Stage - Spent HTF to


Overall Schematic - Propylene Glycol (residential)
Process plan:Reference quantities
The names of the basic processes are shown.
Selection: Overall Schema
Trans reflects matl's sourcing within 100 mi
Tranpostation of HTF to Install site -- 620 Miles
Use Stage-- Assumes total of 0.1% maintenance per year.
US: Diesel mix at filling station ts
US: Electricity grid mix ts
US: Diesel mix at filling station ts
US: Electricity grid mix ts
DE: Propylene glycol ts
US: Truck - TL/dry van (EPA SmartWay)
US: Glycol Mixer V.2 <u-so>
2018 mfg data
US: Truck - TL/dry van (EPA SmartWay)
US: Residential Control of Temp (Glycol) V.2 <u-so>
Residential/Office Scenario
140 L system
Propylene Glycol - 14,930 kWh
200 m2 Area
EU-28: Potassium Phosphate Model
US: Truck - TL/dry van (EPA SmartWay)
EU-28: Tap water from groundwater ts
Maintance Additions of Product
US: Glycol Mixer (Maint) V.2 <u-so>
US: Truck - TL/dry van (EPA SmartWay)
Reusable Packaging
DE: Polyethylene High Density Granulate
US: Truck - TL/dry van (EPA SmartWay)
IBC Pkg - 945 L (250 gal) V.2 <u-so>
US: (C1-C4) HTF EOL Stage - Spent HTF to
GLO: Steel hot dip galvanized (ILCD)
US: Truck - TL/dry van (EPA SmartWay)
Pkg to Reuse <u-so>