Façade-Integrated Mechanical Systems (FIMS): A New Approach for Non-Invasive Deep Energy Retrofits

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ABSTRACT

The HVAC industry will play a critical role in the transformation of the built environment to eliminate harmful emissions, improve indoor environmental quality, and increase housing affordability. Retrofitting existing buildings to achieve these goals has proven to be too expensive and too invasive to be implemented at the large scale necessary using current technologies. This paper introduces the concept and engineering principles behind a new category of HVAC system called Façade-Integrated Mechanical Systems (FIMS) which can be installed over the facade of an existing building with minimal disturbance to the tenants inside. FIMS offer improved overall performance compared to existing retrofit technologies while applying the principles of industrialized construction and modular assembly to reduce costs and shorten project schedules. By simplifying retrofit logistics and offering an attractive return on investment, FIMS enable the widespread implementation of deep energy retrofits at the scale necessary to meet global emissions targets while improving indoor air quality and increasing the affordability of high-performance housing. This paper describes FIMS as applied to multifamily retrofits, though the concept is applicable to a broad range of building typologies and offers similar benefits when applied to new construction.

INTRODUCTION

The HVAC industry will play a critical role in the transformation of the built environment to meet the urgent needs of the 21st century. These include the achievement of net-zero emissions, the provision of healthy indoor environments, and the widespread availability of affordable housing. With roughly 70% of America's 2050 building stock already in existence today (Egerter et al. 2020), retrofitting existing buildings to meet these higher standards must be a priority for the construction industry. While new buildings must also meet these higher standards, existing buildings pose the bigger challenge as a majority of them must undergo deep energy retrofits (DERs) with existing tenants remaining in place (IEA 2011). For older buildings, DERs typically must include significant upgrades to the building thermal envelope, as well as replacement of the existing heating, ventilation, and air conditioning (HVAC) infrastructure. Achieving net-zero emissions requires that fossil-fuel based heating systems be replaced with emissions-free alternatives, such as electric heat pumps that can be supplied from an electrical grid powered by 100% renewable electricity. The need to perform such retrofits in a non-invasive manner that minimizes disruption to tenants and keeps buildings operational during construction is a relatively new challenge for the industry and requires new solutions to make them economically and logistically viable at the scale necessary. The purpose of this paper is to introduce a new category of HVAC system known as Façade-Integrated Mechanical Systems (FIMS) that the author developed to directly address this retrofit challenge. While broadly applicable to new construction and retrofits in a range of climates, this paper focuses on the application of FIMS to DERs of multifamily buildings in cold climates.

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CENTRALIZED VS. DECENTRALIZED HVAC SYSTEMS

When selecting HVAC systems for multifamily buildings, designers often face a trade-off between the higher performance of central systems and the lower cost of decentralized unitary equipment. Central systems generally provide better efficiency, indoor air quality, and thermal comfort, along with the benefits of centralized maintenance and more advanced equipment features (ASHRAE 2020). However, decentralized unitary equipment is often chosen when installation cost is the primary concern for the building owner or developer. For tenant-in-place retrofits, central systems face the additional cost and logistical challenges associated with routing distribution ductwork and piping through occupied spaces. The cost of central HVAC systems can be significantly reduced by following the broader construction industry trend towards industrialized construction methods, with a focus on prefabricated and modular components that can leverage technology to reduce manufacturing costs, improve quality, reduce installation time, and minimize the amount of labor required on site (McKinsey 2017). For DERS, a modular HVAC system installed on the exterior of the existing facade allows for the replacement of existing HVAC systems with a high-performance central system without causing major disruption to the tenants or requiring complex coordination within the building.

SYSTEM DESCRIPTION

A Façade-Integrated Mechanical System (FIMS) is herein defined as a centralized mechanical system in which the heating, cooling, and ventilation distribution, as well as the terminal equipment delivering that conditioning to the space, are completely integrated into the building façade such that no HVAC components are required within the conditioned space. FIMS offer a wide range of economic, logistical, and performance benefits compared to traditional systems and require a new approach to the way HVAC systems are designed, manufactured, installed, and operated.

The Building Facade

To deliver a high-performance building using FIMS, the façade must be highly insulated and tightly sealed to minimize the transmission of heat, air, water, and vapor through the building envelope. This minimizes the heating and cooling demand on the HVAC system, thereby minimizing energy consumption as well as the size, weight, and capacity of the HVAC equipment and distribution, a key factor for integration of the HVAC components within a compact façade assembly. For DERs that include electrification of existing fossil fuel-based heating systems, load reduction is critical in order to reduce or eliminate the need for major electrical service and distribution upgrades within the building, as well as avoiding the costs associated with upgrading the regional electrical grid and adding new generation capacity (IEA 2021). The costs associated with achieving a high-performance facade can be offset by the cost savings resulting from smaller HVAC equipment, avoided electrical upgrades, and lower operating costs.

Adding insulation to the interior side of a perimeter wall is highly disruptive to the tenants, reduces the occupiable floor area, and is ineffective at eliminating thermal bridging to the exterior. Interior insulation also alters the moisture balance and drying capacity of the existing facade, potentially increasing the risk of deterioration and damage from freeze-thaw cycles and interstitial condensation (Webb 2017). Applying new insulation to the exterior provides both performance and logistical advantages while minimizing risks, making it the preferred approach for most DERs. In particular, the use of prefabricated overclad façade panels has proven to be a highly effective method that reduces overall costs and installation time when compared to traditional methods that require extensive on-site labor to manually apply individual components of the façade (Egerter et al. 2020). Many examples of such panelized overclad retrofits can be found throughout Europe (IEA 2017), with similar opportunities for widespread application in the growing DER markets of North America (Salonvaara, 2020). FIMS can be integrated into a wide variety of facade products with a vast array of material options such that the performance and appearance of the new façade can be tailored to the specific needs of each building and local market factors. Key criteria to consider when choosing façade materials include cost, weight, durability, fire resistance, maintenance requirements, and embodied carbon.

Façade-Integrated HVAC

Façade Cavity. For DERs using FIMS, the overclad façade is installed with an offset from the existing façade to form a narrow cavity in which the HVAC distribution and terminal equipment is located (**figure 1**). Fire-resistant barriers are installed within the cavity where required to prevent the spread of fire and smoke, as well as preventing the vertical migration of air within the cavity from lower to higher floor levels due to thermal buoyancy. The depth of the cavity is typically determined by the depth of the duct risers which should be minimized by using higher aspect ratios than are typical of traditional systems. Duct and pipe crossovers should be avoided to minimize overall depth.

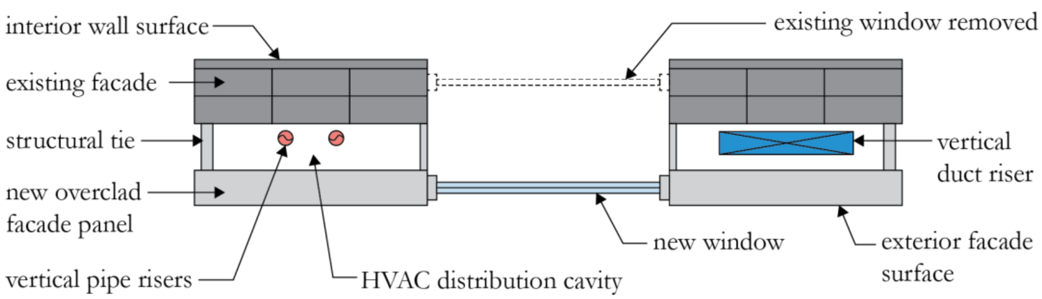

Figure 1 Plan view of a wall section showing the new façade forming a cavity for HVAC distribution.

The cavity is within the thermal envelope formed by the new façade, thereby eliminating the risk of pipe freezing from exposure to outdoor temperatures, while also allowing the option of eliminating duct and pipe insulation entirely. In fact, heat loss from the piping may be desirable and enhanced such that the façade cavity becomes heated or cooled, allowing the heat to transfer through the existing façade and creating a radiant conditioning effect from the perimeter wall to the occupied space. In many cases this radiant heat transfer will be sufficient to satisfy the full heating demand of the space throughout all or most of the heating season. A small amount of conditioned air from the central ventilation system may be supplied directly into the cavity in order to create a positive pressure relative to the outdoors to prevent infiltration as well as to dry out any moisture that may migrate into the cavity.

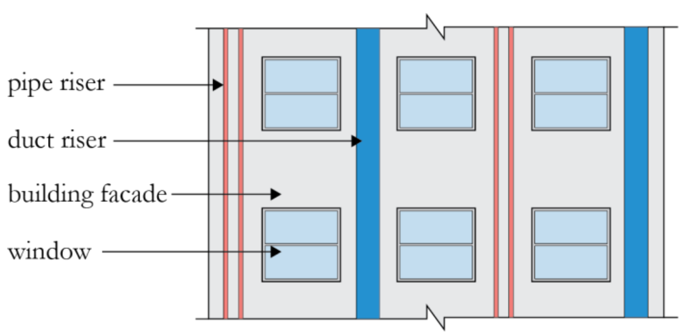

Figure 2 Façade elevation showing vertical duct and pipe distribution risers between windows.

HVAC Distribution. Duct and pipe risers run vertically between the windows to distribute air and water from the central equipment to the terminal equipment serving each conditioned space (**figure 2**). The low internal heat gains and ventilation requirements typical of most residential buildings enables compact duct and pipe sizes that minimize the required depth of the cavity, even in tall buildings where each riser may be serving many floors. Automatic balancing dampers and flow regulating valves may be used to ensure balanced air and water distribution throughout the height of the building. Sizing the ductwork for static-regain along the length of the riser will further help with achieving balanced air distribution and minimizing fan energy consumption. FIMS are well suited to hydronic heating and cooling distribution using water rather than refrigerants. A water-based system is preferred due to the many challenges and risks associated with refrigerants (ASHRAE 2021), especially when applied to large buildings with greater refrigerant quantities and longer refrigerant pipe lengths. Such risks include the environmental impact of refrigerants leaked to the atmosphere, as well as the toxicity and flammability risks associated with refrigerants leaked to the building interior (ASHRAE 2019). Refrigerants also create the risk of additional costs associated with future phase-outs as governments seek to protect against the harmful impacts of current refrigerants (NREL 2020). The hydronic piping may be arranged as a two-pipe changeover system, or a four-pipe system for simultaneous heating and cooling availability, depending on the needs of the specific application. In cold climates, piping on the roof must be insulated and provided with a means of freeze protection such as electric heat tracing.

Central Equipment. Hot and chilled water is generated by central equipment that can take on a variety of different forms, including district thermal networks, ground-source heat pumps, or air-source heat pumps. In most cases, air-source heat pumps will be located on the roof, though for taller buildings equipment may also be located at intermediate floors or at ground level to reduce the length of vertical distribution risers. The capacity requirement of the central heat pumps is minimized by the relatively low loads present in well-insulated residential buildings, as well as by the application of diversity factors to those loads. To simplify installation and reduce costs, heat pumps may be delivered in prefabricated packages that include distribution pumps, factory-wired controls, and hydronic accessories. Central heat pumps also present the opportunity to recover the heat rejected from cooling loads for transfer to heating loads such as domestic hot water, thereby greatly increasing the overall efficiency of the system.

A mechanical ventilation system to deliver conditioned outside air and remove contaminants is essential for maintaining healthy indoor air quality, especially in a building with a tightly sealed façade that prevents infiltration (Logue 2013). FIMS include packaged air-handling units (AHUs) to provide tempered, filtered, and dehumidified ventilation air to each apartment. The AHUs can utilize air-cooled direct-expansion heat pumps, water-cooled condensers, or hydronic coils. Exhaust air from kitchens and bathrooms is returned to the AHU for enthalpy recovery to the incoming air stream prior to discharge. New exhaust risers can be integrated into the façade similar to the supply risers, or for existing buildings, internal exhaust risers may be re-used and connected to the new AHU. Exhaust airflows should be balanced with supply to maintain neutral or slightly positive pressure within each apartment.

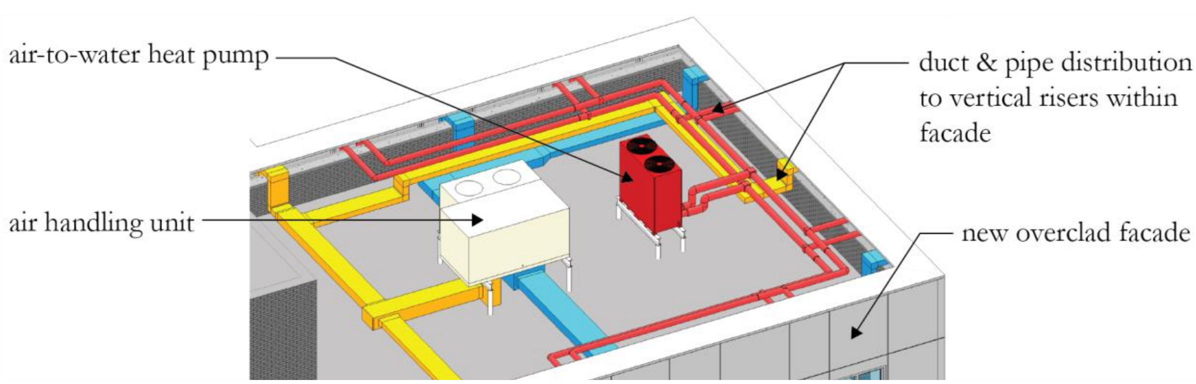

Figure 3 Typical rooftop equipment layout including heat pump, AHU, and duct and pipe distribution.

With roof-mounted equipment, the ductwork and piping are distributed horizontally along the roof surface to the building perimeter where they enter the façade cavity for vertical distribution (**figure 3**). For buildings with large footprints, the central equipment can be divided into zones, with each zone dedicated to a separate section of the building (**figure 4**). This reduces the size of the equipment as well as the size and length of the duct and pipe runs. Smaller distributed equipment reduces the structural point loads on the roof and minimizes visibility from the street.

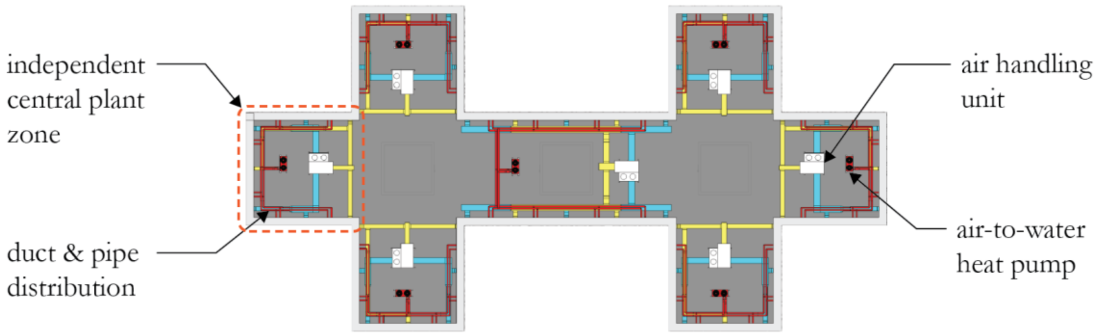

Figure 4 Roof plan showing central equipment divided into zones for a large building footprint.

Terminal Equipment. The sensible cooling capacity of the ventilation air and radiant perimeter wall generally will not be sufficient to fully condition the interior space. Therefore, it is typically necessary to provide facade integrated terminal units (FITUs) in zones where additional capacity is needed. The FITU includes a hydronic coil with a thermostatically controlled valve, as well as a means of recirculating room air over the coil. The FITU is given a narrow form factor such that it can fit within the facade cavity. The extension of the windowsill is a suitable location for the supply and return grilles (**figure 5**). The FITU should be designed such that removal of the grille allows easy access to all internal components for maintenance and replacement. In order to eliminate the challenges associated with condensate disposal during cooling, it is appropriate to design the FITU as a sensible-only device, with the dehumidified ventilation air providing the full latent cooling capacity for the space. Additional control measures may be implemented in cases where the risk of condensation is a concern (ASHRAE 2015).

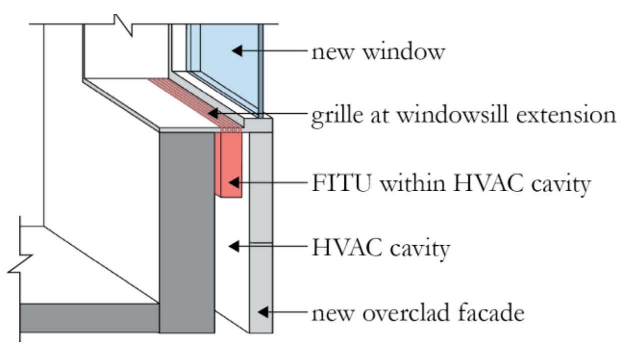

Figure 5 Perimeter wall section showing the FITU location within the façade cavity and the windowsill grille.

Design and Implementation

Design Parameters. The design parameters and operational strategies for FIMS differ in several aspects from more traditional HVAC systems. The highly insulated and tightly sealed façade minimizes perimeter heating and cooling loads. The low loads combined with the efficient delivery of conditioning from the radiant wall and FITU enable the heating and cooling water to be supplied at relatively mild temperatures. The system can be designed such that hot water supplied in the 85 to 95°F (29 to 35°C) range is sufficient to meet heating loads on a design winter day. During cooling, chilled water to the sensible-only FITU is supplied slightly above the space dewpoint in the 58 to 60°F (14.5 to 15.5°C) range to avoid condensation. The mild water temperatures minimize heat loss from uninsulated piping, while minimizing thermal expansion and contraction of the piping during heating and cooling change-over.

Unlike traditional multifamily HVAC systems, the dehumidification of the space is decoupled from the sensible cooling. Conditioned ventilation air is supplied with a maximum dewpoint in the range of 50 to 55°F (10 to 13°C) and in quantities to ensure the latent load is satisfied, which may be up to twice the flowrate required to meet ventilation code requirements. The designer should strive to supply the ventilation air at as low a dewpoint as practically possible in order to reduce the total airflow requirements and associated duct sizes. The room air dewpoint must be maintained below the chilled water supply temperature unless a means for condensate disposal is provided. The ventilation air can be supplied at a neutral temperature in the range of 68 to 78°F (20 to 25°C) with a form of free reheat, such as hot gas reheat, to be utilized when the supply air requires subcooling for dehumidification. Alternatively, desiccant dehumidification may be utilized to achieve the desired supply air dewpoint. The ventilation air temperature can be adjusted up or down when beneficial for space conditioning. When designing FIMS as a two-pipe change-over system, the ventilation air can provide cooling when the water is in heating mode, and vice versa. For example, when cold outdoor temperatures generate heating demand, hot water can be circulated in the piping while the ventilation air can be supplied at 50°F (10°C) such that cooling is available to spaces with cooling demand.

Design, Fabrication, and Installation. One major challenge of traditional DERs is the need for bespoke solutions tailored to the conditions of each individual building (Ma et al. 2012). By eliminating the need for survey and installation work inside the building, FIMS present the opportunity to apply the principles of industrialized construction to simplify the retrofit process and generate a repeatable strategy that can be scaled broadly to buildings of different shapes and sizes. Digital scanning is implemented to ascertain the dimensions of the existing façade that are used to size the new overclad panels in a process that can be highly automated. Locating the HVAC distribution within a dedicated cavity and arranging the ductwork and piping in a simple and repeatable pattern eliminates the need for complex coordination and allows much of the HVAC design process to be automated using simple algorithms. Fabrication of the panels can proceed through a highly automated process that allows easy customization of the panel dimensions to suit each individual project (Barco 2017). Panel fabrication within a factory setting allows for the application of advanced manufacturing technologies that improve worker productivity, thereby reducing costs and improving quality while also providing safer and more comfortable working conditions compared to on-site labor.

Installation of the façade panels is performed from the exterior of the building, including sealing of the panel joints and connection of duct and pipe branches between the panels. The panels can either directly attach to the existing building structure or be implemented as a self-standing construction (IEA 2011). Access to the building interior is only required for removal of the existing windows and for application of finishes around the new window openings. Depending on the chosen electrical distribution strategy, access to the interior may also be required for running new power wiring to the FITUs or to the new central equipment. The span of each modular panel should be sized to minimize the number of panel connections while considering logistical constraints related to panel shipment and hoisting. The panel design should include a simple means of access to the ductwork and piping from the exterior.

DISCUSSION

Benefits of FIMS. One of the key benefits unique to FIMS is that integration of the mechanical system within the façade allows installation to occur almost completely from outside of the building, thereby enabling DERs that minimize the disturbance to existing tenants and that eliminate the need for temporary tenant relocations. Exterior installation also avoids the risks associated with unforeseen interior conditions and minimizes the measures needed to protect the interior space from dust and debris. The result is significant cost reductions and simplified logistics that shorten the project timeline and reduce risks compared to the installation of HVAC systems within an occupied space.

The heating and cooling energy consumption of FIMS is minimized by the highly insulated and tightly sealed façade that reduces heating and cooling loads, as well as the electric heat pumps operating at high efficiency due to the relatively mild water temperatures required. An air-source heat pump generating hot water at 90°F (32°C) can operate at up to 60% higher efficiency than the same heat pump generating hot water at 120°F (49°C) (Arpagaus et al. 2018). The efficiency improvement in cooling can be over 20% when generating 60°F (15.5°C) chilled water as compared to 44°F (6.7°C). Such efficiency improvements combined with the transition from fossil fuels to electricity as the heating source enables the building to achieve net-zero CO_2 emissions when powered by on-site renewables or when the local electrical grid reaches 100% renewable generation. DERs with FIMS can significantly reduce the building's peak electrical demand, making additional electrical capacity available for other electrification measures, such as domestic hot water heating or electric vehicle charging, without requiring an upgrade to the building electrical service.

Thermal comfort is greatly enhanced by the radiant conditioning effect at the perimeter walls and by the decoupling of latent cooling from sensible cooling. The continuous supply of dehumidified ventilation air ensures that space humidity is controlled while the sensible capacity of the FITU is thermostatically controlled to maintain a comfortable space temperature. The filtered ventilation air ensures that excellent indoor air quality can be maintained at all times, resulting in significant benefits to occupant health and cognitive function (Taylor et al. 2021). The thermal capacity of the perimeter walls when heated or cooled from the façade cavity allows the central equipment to be turned off for periods when electric demand reduction is desirable. The thermal energy stored within the walls maintains thermal comfort while the demand reduction can significantly reduce electricity costs. In the event of heating loss resulting from a power outage or equipment failure, the thermal capacity of the walls extends the time that thermal comfort is maintained so that tenants can remain in place until heating is restored (Oberg et al. 2021).

Remote central plant equipment allows major maintenance operations to occur away from the occupied space while also ensuring that major equipment noise is isolated from the occupied space. Maintenance procedures for the FITUs are simple, infrequent, and non-disruptive to occupants. With hydronic distribution, all refrigerants are contained within the remote central equipment, reducing refrigerant quantities compared to refrigerant-based distribution systems and eliminating the risk of refrigerant leaks within the occupied space. Integrating all HVAC components within the façade provides significant benefits for the interior design by eliminating the ducts, pipes, and equipment from the interior, as well as associated shafts, soffits, and mechanical closets. For DERs, FIMS allow the removal of existing HVAC distribution and equipment to regain floor space within the apartments and within existing boiler rooms. The façade cavity used for duct and pipe distribution will generally have ample space for routing of additional services, such as wiring for high-speed internet or a building management system, as well as electrical conduit serving new components within the façade, such as photovoltaic panels, security cameras, or exterior lighting.

Economics. Attractive economics are necessary for any DER solution to achieve widespread adoption. However, the economics of DERs are challenging because they typically require a scope of work beyond the simple measures that provide a quick payback (Zhivov et al. 2015). This is especially true when converting heating systems from low-cost fossil fuels to more expensive electricity, which can increase operating costs if not accompanied by load reductions. DERs with FIMS offer significant reductions in energy costs as well as costs related to the maintenance of outdated HVAC systems and deteriorating masonry facades, especially for buildings in poor condition with high pre-retrofit operating costs. Additional cost benefits are realized when legislation imposes a price on CO_2 emissions and allows for revenue through the sale of emissions credits. Improvements in indoor air quality, thermal comfort, interior acoustics, and a revitalized building appearance all increase the marketability of a building, creating value in the form of higher occupancy rates, reduced turnover, and increased rental prices (Leskinen et al. 2020). Additional strategies such as postponing a DER until existing HVAC equipment needs replacement can further enhance the economics.

FIMS installation costs can be significantly lower than traditional retrofit approaches by eliminating HVAC work from inside the building and by leveraging the benefits of prefabrication and modular assembly that improve productivity and reduce on-site labor requirements. Project costs can be further reduced through the application of advanced manufacturing and automation technologies to the design and fabrication process. Combining the economic benefits of FIMS with low-cost financing presents the opportunity for building owners to finance a FIMS DER with loan payments that are lower than the newly generated cash flow, while also creating the opportunity for off-balance-sheet financing options such as energy service agreements provided by turnkey solution providers (Calder 2020).

Applications. FIMS are ideally suited for dwelling units in multifamily apartment buildings, hotels, and dormitories, which generally have low internal heat gains and ventilation requirements, as well as shallow floorplates that allow for complete conditioning from the perimeter. Common areas such as corridors, lobbies, and other amenity spaces may require separate HVAC systems due to higher loads or greater distance from perimeter walls. FIMS may be applied to many other building typologies, though for buildings with deep floor plates and higher internal gains, FIMS may be dedicated to perimeter zones and supplemented with internal HVAC systems for interior zones. With HVAC components integrated into the opaque portions of the façade, FIMS may not be suitable for buildings with high window-to-wall ratios. Facades with a regular pattern of punched windows are ideal for the distribution of vertical duct and pipe risers between the windows and the placement of FITUs below the windows. Flat roofs are ideal for the placement of central equipment, though equipment can also be located within mechanical rooms or on grade. Buildings with extensive roof setbacks or rooftop amenity space may have limited area available for rooftop equipment and therefore may require that central equipment be located in alternative locations. FIMS are well-suited for tall buildings, though the size of duct and pipe risers increase in proportion to the number of floors served. Longer duct and pipe runs can increase fan and pump energy while making balancing more difficult between higher and lower floors. For these reasons, tall buildings may be divided into vertical zones with central equipment provided at intermediate floors as is common for traditional HVAC systems in tall buildings (Simmons 2015).

FIMS offer compelling benefits for both retrofits and new construction. For retrofits, the existing building must be evaluated against several criteria to determine if FIMS is an appropriate solution. Such criteria include the availability of roof or other space for central equipment, the window-to-wall ratio, the shape and arrangement of windows, as well as any physical or regulatory limitations on expanding the depth of the façade. The building structure must be evaluated for available loading capacity and suitable attachment methods. Balconies can complicate the façade design and installation, depending on their extent and arrangement, while also acting as a thermal bridge that degrades thermal performance. There are several options for accommodating balconies, including enclosure within the new façade to create a semi-conditioned interior space that tenants may prefer over an exterior balcony (Sheehan 2017). The application of FIMS to new construction is greatly simplified by allowing the building design to be optimized for effective equipment placement and HVAC distribution. The use of FIMS for new construction is particularly compelling as it can offer better overall performance at lower installation cost when compared to traditional HVAC systems. As tens of millions of new housing units are built every year for growing populations around the world (Cheong et al. 2019), FIMS present the opportunity to do so in a manner that is both efficient and affordable, and that provides the levels of indoor air quality and comfort that are typically only achieved in more expensive luxury housing.

CONCLUSION

Locating HVAC systems within the façade, instead of the building interior, greatly simplifies the process of design and installation for both retrofits and new construction. FIMS are ideally suited for prefabrication and modular assembly that reduce costs and installation time while achieving better quality and performance. FIMS enable non-invasive building retrofits that avoid many of the costs and complications associated with performing work within an occupied space. FIMS can be the sole source of conditioning for spaces dominated by perimeter loads and can be supplemented by interior cooling and ventilation systems for application to a broad range of building typologies. FIMS represent a new approach to HVAC system design and construction that will enable better performance at lower cost than traditional methods, thereby playing an important role in the transformation of the construction industry as it adapts to meet the environmental, social, and economic challenges of the 21st century.

REFERENCES

Arpagaus, B., Bless, F., Uhlmann, M., Schiffmann, J., and Bertsch, S. 2018. High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potentials. *International Refrigeration and Air Conditioning Conference*. Paper 1876.

ASHRAE. 2015. *Active and Passive Beam Application Design Guide*. Atlanta: ASHRAE

ASHRAE. 2019. *ASHRAE Standard 34 - Designation and Safety Classification of Refrigerants*. Atlanta: ASHRAE.

ASHRAE. 2020. *ASHRAE Handbook - Systems and Equipment*. Atlanta: ASHRAE.

ASHRAE. 2021. *ASHRAE Handbook - Fundamentals*. Atlanta: ASHRAE.

Barco, A., Vareilles, E., Gaborit, P., Aldanondo, M. 2017. Building Renovation Adopts Mass Customization: Configuring Insulating Envelopes. *Journal of Intelligent Information Systems*. Springer Verlag, pp.119-146.

Calder, D. 2020. *The Case for Deep Retrofits: Improved Business Case Evaluation and Financing Options for Deep Retrofits in Multi-Unit Residential Building*. Toronto, ON: The Atmospheric Fund.

Cheong, C., Storey, D. 2019. *Meeting Global Housing Needs with Low-Carbon Materials*. Seoul: Global Green Growth Institiute.

Egerter, A., and Campell, M. 2020. *Prefabricated Zero Energy Retrofit Technologies: A Market Assessment*. Oakland, CA. DOE/GO-102020-5262.

IEA. 2011. *Retrofit Strategies Design Guide: Advanced Retrofit Strategies & 10 Steps to a Prefab Module.* International Energy Agency

IEA. 2017. *Deep Energy Retrofit – Case Studies*. New Buildings Institute.

IEA. 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector.* International Energy Agency

Leskinen, N., Vimpari, J., and Junnila, S. 2020. A Review of the Impact of Green Building Certification on the Cash Flows and Values of Commercial Properties. *Sustainability*, 12, 2729; doi:10.3390/su12072729

Logue, J. 2013. Energy Impacts of Envelope Tightening and Mechanical Ventilation for the U.S. Residential Sector. *Lawrence Berkeley National Laboratory*. LBNL-6053E.

Ma, Z., Cooper, P., Daly, D., & Ledo, L. 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and buildings*, 55, 889-902.

McKinsey. 2017. *Revinventing Construction: A Route to Higher Productivity*. McKinsey Global Institute

NREL. 2020. *Refrigerants: Market Trends and Supply Chain Assessment*. Golden, CO. NREL/TP-5500-70207.

Oberg, B., Urban, A., Leffel, E., Goebel, J., Perry, M., Vas, D., Broderson, D., Liesen, R., Zhivov, A. 2021. Thermal Energy System Resilience: Temperature Decay in Cold/Arctic Climates. *ASHRAE Transactions*, v.127, 2.

Salonvaara, M., Aldykiewicz, A., Hun, D., Desjarlais, A. 2020. Cost Assessment of Building Envelope Retrofits. *Proceedings of the ACEEE 2020 Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA.

Sheehan, A., 2017. *The Effect of Balcony Enclosure Retrofits on the Performance of MURBS*. Toronto: Ryerson University.

Simmons, P., 2015. *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems*. Atlanta: ASHRAE

Taylor, M., Rim, D., 2021. Review of the Effects of Indoor Air Quality on Occupants. *ASHRAE Transactions*, v.127,1.

Webb, A. L. 2017. Energy Retrofits in Historic and Traditional Buildings: A Review of Problems and Methods. *Renewable and Sustainable Energy Reviews*, 77, 748-759.

Zhivov, A., Lohse, R., Shonder, J., Nasseri, C., Staller, H., Moerck, O., Nokkala., M., 2015. Business and Technical Concepts for Deep Energy Retrofit of Public Buildings. *ASHRAE Transactions*, v.121,2.