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PROJECT REPORT

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NeGeV: next generation energy efficient ventilation system using phase change materials

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Abstract

Product development in the HVAC business segment are continually showing disturbingly slow annual increases in product performance, gradually reducing profitability in the market. Cooling and heating technologies applied in the HVAC industry range from simple natural cooling to more advanced active solutions based on conventional compression technology, but the performance increase is fundamentally incremental. This paper presents the NeGeV project which will provide an innovative solution demonstrating a leap in ventilation systems performance through the use of phase change materials for active heat recovery during periods of cooling needs. The project will develop, design and produce a prototype system and document its performance through certified tests. Through development of intelligent controls for the system, the project will demonstrate the potential for system integration into a smart grid application of load shifting and optimal operation control. In addition, the technical and economic feasibility of the prototype will be evaluated considering an office-space case study.

Keywords: Energy efficiency, Buildings ventilation, Phase change material, Intelligent control

Introduction

Buildings worldwide consume about 35–40% of the overall energy consumption while contributing to a substantial amount of the CO2 emissions (Jradi et al. 2018). Aiming to achieve the ambitious energy and climate objectives in 2020 and 2050, the European Union lists the building sector as a priority in terms of improving the performance and cutting the energy consumption and operational costs and emissions. This has led to new and upgraded building regulations and standards to take effect in the majority of the countries with very strict constraints on energy levels and indoor comfort (Annunziata et al. 2013). With the current building trends, using a lot of glass in modern buildings and increased focus on indoor climate, the HVAC industry experiences an increased demand, especially for turn-key solutions with integrated cooling. In Europe, the number of buildings with space cooling demands is increasing dramatically in the recent decades aiming to obtain good thermal comfort and indoor air quality especially in warm summer periods. Thus, the estimated installed cooling capacity by 2025 is expected to increase by around 55–60% compared to 2010 numbers (Werner 2016). However, the European HVAC industry is facing difficulties in optimizing current technologies sufficiently to live up to current and expected future regulatory restrictions concerning energy consumption and carbon footprint. Due to the highly competitive market, R&D investments in the HVAC-industry are limited, with a short time-to-market and a conservative risk profile, with a very limited uptake of new technologies.

Due to these factors, technological development in the HVAC industry is historically only incremental, focusing on cost down initiatives and improving existing technology. Nevertheless, latent heat storage has been qualified as one of the most efficient ways to store thermal energy, with higher storage density and smaller temperature changes, when storing and releasing the heat (Jradi et al. 2013). Since the 1980's, Phase Change Materials (PCMs) attracted an abundance of research owing to the steady melting/freezing heat storage in a narrow temperature range; the wide range of applications, and the high thermal density. PCM suppliers have already pointed to the potential in using PCM in HVAC solutions, but so far without interest from the HVAC industry due to the aforementioned hard marked competition and conservative sector. The Next Generation Ventilation (NeGeV) project described in this report will aim to demonstrate a leap in performance through the use of PCM's for active thermal energy recovery to provide the ventilation and cooling demands of an office application case.

The NeGeV project addresses two strategic areas of the Danish Energy Agency (Danish Energy Agency 2017), as the NeGev offers significant energy reductions, while also offering the storage potential in PCMs to balance the electricity grid.

In the project, specific recommendations from the Danish Energy Agency report "Status and recommendations for RD&D on energy storage technologies in a Danish context" (Schrøder 2014) are addressed, where it is concluded that:

- new, cheaper and more effective materials should be developed for use as PCM.
- energy density of complete thermal energy storage systems should be increased by use of more compact system designs and better storage materials.
- improving heat conductivity of storage materials is important because the conductivity sets a limit for the rate at which heat can be charged and discharged for a storage facility/system.

The project is an industry driven, but university headed energy development and demonstration project. It started on April 1'st 2018 and will run for 3 years. It combines three industrial companies, a technological institute and a university. It is funded by the Danish Energy Agency under the Energy Technology Development and Demonstration Program (EUDP Project no 64017-05117).

State of the art

Cooling/heating technologies applied in the HVAC industry ranges from simple natural cooling to advanced Direct Expansion (DX)-solutions, and all active cooling solutions are still based on the use of refrigerants in compressor-based systems, where the best available technology are systems with high efficiency compressors and less harmful refrigerants. The conventional active HVAC systems are characterized by high energy consumption, high investment and operation costs, low flexibility and large greenhouse gas emissions (Best and Rivera 2015). The introduction of Eco design renders many of the existing product lines obsolete, forcing the industry to develop new, more efficient products. Thus there is an increasing need to improve the energy efficiency of the built environment without compromising the indoor air quality and thermal comfort levels. This has resulted in the development of various techniques of better usage and conservation of energy for HVAC applications in buildings.

In addition, with the tight regulations and standards regarding HVAC systems and the limitations on the use of conventional systems with harmful refrigerants and working fluids, there is a large potential for environmentally friendly HVAC solutions making use of efficient and innovative technologies.

The potential of PCM as an eco-friendly solution in balancing energy oscillations in a building has been addressed in a number of scientific articles and experimental cases (Kasaeian et al. 2017). The majority of the work concerning the use of PCM for air conditioning in buildings have been concentrated on passive solutions (Ning et al. 2017), mainly integrating the phase change material within the building envelope components. Integrating PCMs in building components like plaster, gypsum board, concrete, and other building envelope materials has been investigated extensively in the literature and tested in projects (Microtek Lab. 2018), (Karaipekli and Sarı 2016).

While passive HVAC applications in buildings employing PCM have been widely investigated and implemented, active solutions and systems are still less mature. PCM-based products are generally on a research and laboratory testing level. So far it has been tested in laboratory settings with promising results and in a few one-off projects, as for example, PCM-Kompaktspeicher project, where a demonstration unit was built in the premises of Rubitherm GmbH, to be supplied with fresh air, which is cooled during the warm summer days by a PCM compact storage device (Stein und Partner 2018).

A number of research and development projects supported by Danish public funding programmes such as ForskEl, EUDP and InnoBooster has explored the potential in using flexibility potential in energy systems (e.g. heat pumps) in balancing the power grid, and also the integration of intelligent buildings is addressed in a series of projects (Energiforskning.dk 2018). There are ongoing projects introducing heat pumps and tele sites on the not yet fully developed demand response market, but this project will be the first to enable companies to introduce and mass market the technical possibility to a wider range of HVAC customers.

Inherent storage capabilities in building energy systems and robustness towards short term fluctuations makes building energy systems an ideal part of the solution to the problem of balancing a system based on renewable energy sources (Danish Ministry of Energy, Utilities and Climate 2016). The use of heat pumps in balancing the electricity grid has been well explored (Sørensen et al. 2013), and numerous projects have been conducted to prove the potential. While entire bulding energy systems are studied in large scale projects (COORDICY 2018), the great potential in ventilation and comfort cooling has yet to be explored on a larger scale in commercial projects. With a combined total energy consumption of 7,6 TJ for ventilation (5,4 TJ) and comfort cooling (2,2 TJ) as compared a total consumption of only 0,6 TJ for heat pumps, the potential in power reductions and flexible consumption is huge (Danish Energy Agency 2015).

Thanks to their substantial latent heat storage capacity, PCMs have a large potential to be employed in active HVAC applications. A large amount of energy can be stored in the isothermal process of melting the PCM, which is what happens when hot air is lead through the PCM module. In Fig. 1, where the principle of using only a sensible energy storage (blue dotted line) is compared to a latent energy storage (solid green line), it is shown that the energy potential is greater when using latent energy storage.

The use of PCM in connection with ventilation systems has been studied in a few earlier investigations. In one study, the PCM is used in a heating application for load shifting during peak hours (Stathopoulos et al. 2016). For that, a prototype of a PCM heat exchanger was built, and a numerical model was developed to study the behavior of the PCM heat exchanger. The study showed that the relatively simple numerical model could accurately reproduce the experimental behavior of the PCM heat exchanger. In another study, PCM was applied in a heat exchanger for a heating application in a ventilation system, to provide load shifting during peak hours (El Mankibi et al. 2015). A numerical model was developed, and a prototype was tested in a rectangular generic room. This study showed that when charging the PCM module at night, the performance of the heat exchanger greatly depended on the insulation of the heat exchanger due to the long periods of time where the PCM should remain charged. And thus, increased insulation prevented involuntary discharging of the PCM. During a large number of test configurations, the study showed that it was possible to perform load shifting without compromising thermal comfort or indoor air quality.

Project objectives

As presented in the background, the use of PCM for heat recovery in active ventilation systems has been investigated in a few studies and promising potential was demonstrated. However, such solution is yet to find a way to the market as additional investigation in terms of design, control and optimization of the system is still needed.

The NeGeV project objective is to develop the next generation of HVAC systems by demonstrating an innovative, cost-effective and scalable solution to provide thermal comfort in buildings. The proposed ventilation system makes use of an innovative

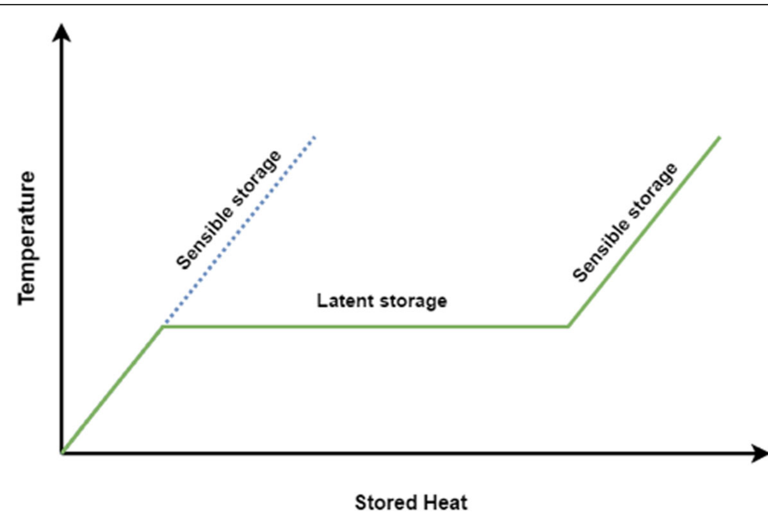

Fig. 1 The principle of using latent energy storage compared to sensible energy storage

PCM based module to provide the cooling needs, replacing the conventional energy-intensive cooling techniques. This will cause an unprecedented increase in energy efficiency and it will decrease the need for environmental harmful refrigerants and working fluids.

Project concept

The project is based on, and will further develop, the most recent research in the use of PCM as a thermal energy storage for balancing temperature oscillations in buildings. The PCM-based thermal storage medium will allow on-demand heat exchange with high efficiency and reduced losses.

The concept of the NeGeV prototype is to use the PCM in a climate module as an energy storage in a decentralized HVAC solution, and having this storage will eliminate the need of using harmful refrigerants in the cooling application as it will replace the relatively expensive DX systems. The overall project concept and the proposed system operation phases are illustrated in Fig. 2 and listed below:

- A climate module containing a rack of PCM panels ensures proper conditioning of the ventilation air.
- The climate module is charged during the night, by having the cold outdoor air directed through the climate module, and thus lowering the temperature of the PCM. During charging the PCM will solidify.
- In case of cooling during the day the supply air is directed through the climate module which absorbs heat and thus discharges the module while cooling the ventilation air. During discharging the PCM melts.
- The module releases heat during the night, or when there is a heating need.
- The only external energy supply is the extra load on the Air Handling Unit (AHU) fan. The climate module adds an increased pressure drop across the ventilation system leading to an increased load on the AHU fan. Optionally, an auxiliary fan can be mounted in the system to help circulate the air. The module should potentially replace an active conventional air conditioning system
- The installed capacity of the unit will enable negotiation of demand response services to the grid.

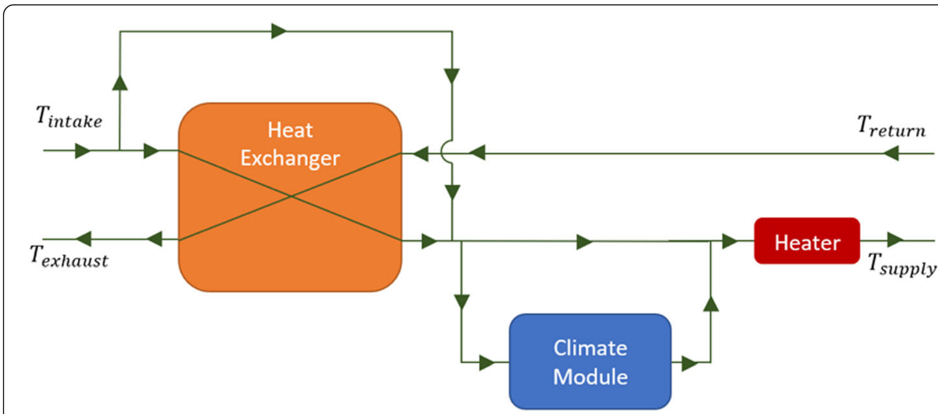

Fig. 2 NeGeV Project Concept

- The capacity of the module can be varied by the number of PCM panels.
- Regarding the phase change materials, the development in the last two decades has mostly targeted available melting temperatures and long-time stability of the PCMs, where the specific storage capacity has been almost stable. So NeGeV will consider the latest developments in the field and will focus on applying the concept on the smaller air volume products - eg. the compact air handling unit family from Exhausto.
- The PCM panels have a lifetime depending on the number of charge/discharge cycles, and can easily be replaced as spare parts in the climate module.

Project methodology and deliverables

The overall project deliverable is the design, development and testing of a full-scale prototype of an HVAC-solution for office applications, with an advanced controller and PCM climate module. The NeGeV prototype will be achieved by developing a PCM-based energy storage module (climate module) with novel heat exchange design. Advanced integrated controls using complex algorithms to forecast and optimize operation will be implemented in the prototype. These will be based on a wide range of data on building latency, outdoor temperature, use patterns etc., making it possible to use building heat capacity, free cooling and the PCM module in combination to optimize the PCM climate module design and enhance the system operation and improve the overall energy efficiency.

The full-scale prototype of a HVAC-solution will in part be built on an existing HVAC-platform (VEX308) which is a low volume stand-alone HVAC solution for classrooms and offices, currently developed by the project partner Exhausto, shown in Figs. 3 and 4. This existing platform is chosen to reduce project costs and technical risks. The current VEX308 unit has been widely implmeneted in school classes and teaching rooms but with limited applications in office buildings. This is due to the high cooling demands in offices and the need for a cooling system. Thus, the proposed NeGeV prototype with its cooling capability will help providing large potential in terms of implementations in office buildings.

The project is broken down into seven work packages (WP's) as listed below.:

WP 1 Defining ventilation system and application
WP 2 System energy balance model

Fig. 3 The VEX308 in a classroom (Exhausto)

Fig. 4 The VEX308 with visible pipes for inlet and exhaust air (Exhausto)

WP 3 PCM-materials and casing
WP 4 Climate module – energy storage, heat exchanger and charger
WP 5 Controller
WP 6 Prototyping and tests
WP 7 Project management and dissemination

All WPs are connected, and therefore work done in one WP is interrelated to other WPs. As seen in Fig. 5, WP 1 is the preliminary WP that leads to the work done in WP 2, 3, 4 and 5. All these 5 WPs will lead to WP 6 where the overall goal of the project is achieved, which is to have an operational and tested prototype. WP 7 will be an ongoing task executed simultaneously with all other WPs.

The specific deliverables of each WP is summarized below:

WP 1: A report defining system, application and scope of the project is to be developed. Several system designs will be investigated to create a basis for choosing

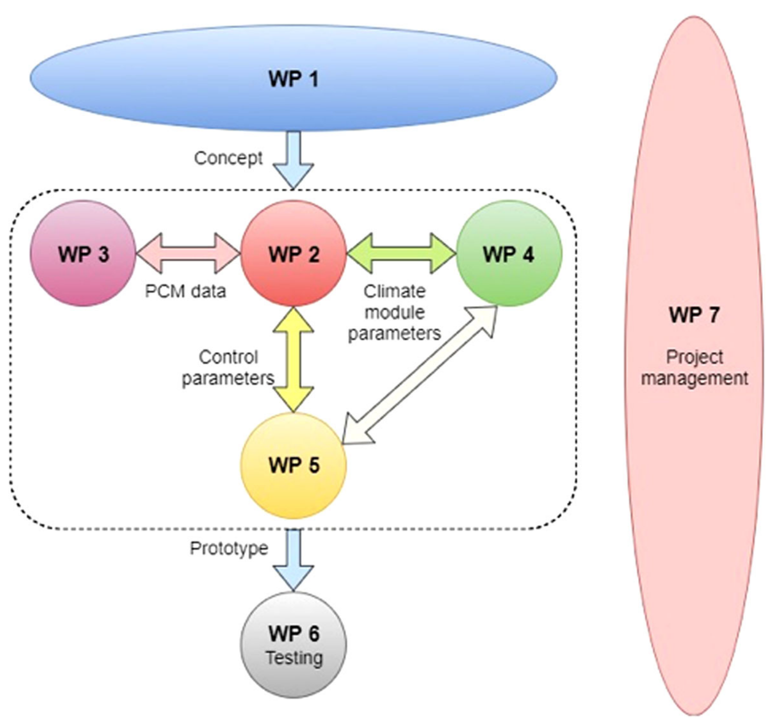

Fig. 5 Diagram showing the connection between work packages

the best system design. In addition, major factors that can play an important role for the successful completion of the project are identified and discussed. Relevant legislation is outlined to make sure that the NeGeV prototype will live up to specified conditions and industrial norms and standards. Moreover, a preliminary quasi steady state model will be developed and the performance of the PCM-integrated ventilation system will be simulated.

WP 2: A complete system energy model will be developed to form a basis of a simulation and design tool suite which delivers clear design, operation and control parameters to predict energy capacity demand and system dynamic performance under given conditions.

WP 3: Suitable phase change material will be highlighted in addition to convenient casing to deliver encapsulated PCM modules to the prototype.

WP 4: A mechanical design of the climate module will be provided with optimized airflow and heat exchange, including CAD drawings, documentation and production method. In addition, a report describing the performance of the climate module under realistic use regimes is to be developed.

WP 5: Development and delivery of an intelligent controller for system and components that is able to integrate and balance all considerations and parameters, in order to take full advantage of the climate module, as well as optimize building energy consumption and make the buildings flexibility potential available to the grid in demand response events.

WP 6: Development and testing of the HVAC-system prototype, integrating components from prior WPs. The AHU/Controller/Climate module prototypes are specified and tested. A report documenting the results will be developed and an optimized system prototype is manufactured.

WP 7: This WP will provide clear project management in addition to coordination of dissemination of results,

Project partners

The project is carried out in collaboration between the industrial partners Exhausto A/S, Lodam Electronics A/S and Rubitherm Technologies GmbH, the Danish Technological Institute and the University of Southern Denmark.

The company Exhausto has for many years been a dominant manufacturer of HVAC systems, as market leader in northern Europe, but covering most of Europe with cutting edge products. Exhausto is known to manufacture innovative, high quality products with high energy efficiency and low environmental impact. The company is the primary end producer of the potential final product and will contribute to the project by supplying application domain knowledge, construction of the prototype and carry out preliminary system tests.

Lodam possesses extensive knowledge and knowhow about developing, producing and implementing innovative and efficient electronic climate control solutions. Lodam is a member of the BITZER Group, one of the largest groups in the global refrigeration and air-conditioning compressor industry. The company aims to gain cutting edge knowledge about the potential issues involved in control of PCM systems and are responsible for WP 5 and the development of the system controller.

PCM partner Rubitherm is one of the leading manufacturers and developers within the PCM industry, working on PCM solutions for a range of applications since 1993. Rubitherm succeeded with supplying PCM-solutions to multiple projects within PCM-based climate regulation in large buildings as well as supplying PCMs for the Monodraught system. Rubitherm has a special focus on encapsulation techniques for PCMs and will be responsible for WP 3.

The Danish Technological Institutes contribution to the project will include the test laboratories for documentation of system efficiency (EnergyFlexOffice) being part of the national Green Lab for Energy Efficient building servicing Denmark and EU. The main contribution is performance tests, but will also contribute with knowledge within Smart Grid and intelligent buildings, in order to enable control of the HVAC to offer both energy cost optimization as well as enable demand response events.

The Department of Engineering at University of Southern Denmark (SDU) participates in the project with an interdisciplinary research and development team from Center for Energy Informatics, featuring both solid scientific knowledge, but also substantial industrial experience, from simulation of energy systems and modeling, as well as simulation and testing of phase change-based systems and R&D project management. In addition, SDU participates with a team of R&D engineers from the mechanical engineering department with strong competences in fluid dynamics and heat exchanger design, mechanical design, drawing and construction. SDU is leading the project and project management and will be responsible for the remaining work packages.

Expected results and impact

The project will demonstrate the first HVAC-solution of its kind in the market utilizing PCM-materials, as well as offering Smart Grid integration. The main impact of the NeGev project will be twofold; Introducing major building systems on the market for flexible energy consumption and reducing overall energy consumption freeing capacity in the entire system.

The major NeGeV project outcome is a full-scale prototype of a HVAC solution for office application, with advanced controller and PCM based climate module. The added value of the proposed innovative system can be summarized by:

- An innovative, cost-effective and scalable solution to provide thermal comfort
- An unprecedented energy efficiency, reducing electricity consumption by 50–90% on cooling/heating compared to standard use of best available technology DX cooling with similar capacity, without any use of refrigerants
- A Smart Grid integration for cost optimized operations

NeGeV will demonstrate the use of an entire HVAC-system as a source of flexible energy consumption, with a potential effect of demand response events, once the technology reaches the market.

Developing the data models and controllers to enable the use of not only the PCMs but entire building latencies in demand response events is quite complex. But once developed, it will be quite easy and cost effective to integrate a vast number of buildings in aggregation software.

With a total annual energy consumption of 2,2 TJ, comfort cooling in buildings is considered by the Dansih Energy Agency as one of the areas with the greatest potential of energy savings (Danish Energy Agency 2015). The potential for energy savings from the use of PCM in cooling and heating has been explored in a number of studies, indicating a great potential with reported savings of up to 73% (Barzin et al. 2015). Combining a PCM module with intelligent controls this project expects to demonstrate a 50–90% reduction in electricity consumption for cooling/heating, compared to standard use regimens of best available technology DX cooling with similar capacity.

The effects on independence from fossil fuels are equivalent to the effects of saved energy. The project will greatly reduce energy consumption for comfort cooling. And since most of the energy used for cooling is consumed during peak load hours, the energy consumption reductions will reduce demand for system peak load capacity. At the same time the NeGeV project will have the potential of delivering balancing without significant system costs and without sacrificing comfort, making the system more robust with regards to power delivery fluctuations from renewable sources.

Cooling and air condition is by far the biggest areas for the use of HFC-gasses (for example R407 with a GWP-index of 1774), and is expected to account for between 7 and 25% of all CO2 equivalent emissions worldwide in 2050 (Danish Environmental protection Agency 2016). In the NeGeV project HFC-gasses will be entirely removed from the HVAC. The project will not only provide an instant reduction in the carbon footprint, equivalent to the market uptake of the new system, but will also demonstrate, to the entire business and to regulating bodies, that significant CO2 reductions are possible and hopefully inspire the global market to stop using environmentally harmful HFC-gasses in comfort cooling solutions.

The project has significantly larger development expenses than usual product development in the market, due to the radical technological innovation presented. But initial cost analysis suggests, that the product will not be more expensive to produce and can be sold with roughly the same (or bigger) profit margins compared to current products. For the customers, the product offers significant operating cost reductions, and even a possible revenue from selling energy flexibility in demand response events in countries with flexibility markets and aggregators.

The prototype will be brought into a product development process for release of a first-generation product. The product will be competitive from its first introduction, matching current price levels and greatly reducing operating costs, while at the same time offering a greatly improved CSR-profile with 50–90% reduced energy consumption and similarly reduced carbon footprint.

Summary

In summary, the NeGeV project offers a possibility of disruptive innovation in the HVAC business segment through development and test of a functioning prototype ventilation system with cooling option based on a PCM climate module.

More information can be found here: https://www.sdu.dk/en/om_sdu/institutter_centre/centreforenergyinformatics/research+projects/negev or by direct contact to the corresponding author.

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Availability of data and materials
NA.

Authors' contributions
CTV made the first draft based partly on the original project application and on subsequent work done by the co authors in the beginning of the project. MJR was a major contributor in rewriting the manuscript into its final form and all authors read, commented and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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