A HYBRID ENERGY GENERATION AND MANAGEMENT PLATFORM FOR ENERGY EFFICIENT SMART BUILDINGS

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ABSTRACT

Energy consumption for building-related services accounts for approximately one third of total EU energy consumption. With hybrid off-the-grid energy generation and management systems, significant energy savings can be achieved, thus helping to attain objectives on climate change and security of supply.

The engineering and deployment of off-the-grid energy production systems for buildings addressing the renewable energy technologies (e.g. wind, solar, geothermal, fuel cells) and integration of these systems with the ICT-based sub-systems becomes a necessity. Integrated IT tool support for these activities does not exist; available tools are stand-alone products, often tied to specific standards. This lack of appropriate descriptions and tools currently outweighs the benefit of software interoperability.

This paper addresses an integrated building concept that operates on energy-efficient basis while capturing retrofit opportunities that scale from a single building to multiple buildings at district level. The proposed concept is developed based on two research areas; (1) Building energy supply-side (micro-grid) management and (2) Building energy demand-side management complementing with the integrated energy production from renewable energy sources, building energy diagnostics and predictive control, ubiquitous wireless sensing technologies, and micro-grid power electronics and power control to exploit the potential for reduction of building energy consumption, thus addressing the deficit of insufficient tool support. To reach this objective, new methods and tools are researched that increase system productivity covering hardware and software design for individual production/consumption sub-systems, system design of component networks and integration into backend systems. The research focuses on an innovative model-driven development approach that integrates systems in building supply-side and building demand-side to balance efficient energy production from off-the-grid systems and optimized consumption. The system integration is based on advanced control algorithms capable of learning from previous operations in real time. The research findings will be demonstrated in an office building in Hannover, Germany integrating different energy efficient production/consumption systems addressing the renewable energy technologies coupled with energy storage systems and building energy management systems comprising scalable and robust sensing network platforms, energy performance monitoring and data warehouse technologies.

Keywords: energy efficiency, smart buildings, BIM, data warehouse technology, wireless systems.

1. INTRODUCTION

Europe's objective under the Kyoto Protocol and Copenhagen Summit is to reduce the level of GHG emissions while also decreasing the current dependence on imported energy. Currently, the EU currently imports 82% of its oil and 57% of its gas, making it the world's leading importer of these fuels. The EU can have little influence on external energy markets and energy supply but can influence domestic energy demand. One possible solution to both the above problems is to reduce energy consumption by improving energy efficiency.

According to European standard "EN 15232 Energy Performance of Buildings-Impact of Building Automation" building operation systems can, depending on building type and equipment standard, produce the following potential savings of energy: restaurants 31%, hotels 25%, offices 39%, shopping centers 49%, hospitals 18%, schools/universities 34% and residential 27% (DIN 2007; VDMA 2008). This is a major contribution to the "Kyoto-Protocol-Process" in which the EU outlined the objective to reduce energy consumption by 20% by 2020.

Also, it is often faster and less costly to integrate building energy systems than it is to insulate building shells. At the moment sophisticated building energy management systems are available for facilities management. Most of the larger non-residential buildings younger than 30 years are already equipped with wired building automation systems in Europe. However, their focus on energy performance rating of buildings is at best sporadic often consisting of an ad-hoc combination of off-the-shelf building management systems (BMS). This ad-hoc combination presents many difficulties for building owners in relation to the management and upgrade of these systems, as the BMS can consist of a number of components utilizing various information exchange protocols that have to be integrated within the monitoring and targeting (M&T) software packages. The optimization of these systems for energy management adds another layer of complexity to the design and management procedures (Nikolaus 2008). It requires analyzing the system, developing new interfaces, replacing devices, and optimizing parameters. Furthermore the engineering and deployment of efficient energy production systems for buildings addressing the renewable energy technologies, phase change materials, energy harvesting facades and integration of these systems with the ICT-based sub-systems becomes a necessity. Integrated IT tool support for these activities does not exist; available tools are stand-alone products, often tied to specific standards, and focus on development from scratch. There is not a procedure defined which describe information exchange between different domains for different energy generation and management systems. This lack of appropriate descriptions and tools currently outweighs the benefit of software interoperability. As this technology gap spans for all application domains, it will likely hamper further adoption of IT solutions. In this regard, the prospective consequence of the building behaviour and the needs of the building occupant/operator which would manage energy production/consumption efficiently would not be predictable with a single combined information, communication, hardware and tool platform. A promising approach, to overcome these shortcomings, is the implementation of a holistic, modular infrastructure for building energy supply and demand sides.

2. APPROACH

The agenda in this research is build on the need of integration structures, holistic monitoring and analysis methodologies, life-cycle oriented management and decision support of both facilities and service teams with considering two key research areas; (1) Building energy supply-side (microgrid) management which addresses the energy management systems capable of optimal integration and control of energy production addressing renewable energy technologies such as photovoltaic/hot water solar panels, geothermal heat pumps, small scale wind turbines, biomass and the communication and intelligence required to work cooperatively with local authorities/grid operators and (2) Building energy demand-side management which comprises a scalable, robust wireless sensing/actuation network platform that computation and actuation to collect build-use data through advance data monitoring and data mining technologies which lead to develop optimal control algorithms that adjust Lighting, Heating, Ventilation, Cooling set points to adapt to occupancy, weather loads and their predictions, minimizing total energy consumption and balancing peak demand while maintaining the indoor environment within user preferred comfort parameters.

The proposed concept is maintained in an integrated approach by developing (1) *middleware for BES* which maintains optimal integration and control of off-the-grid energy generation systems for building energy supply side, (2) *middleware for BED* which consists of a sensing network platform and data warehouse technologies for building energy demand side, and (3) *intelligent control module* consisting of control algorithms for low energy building operation.

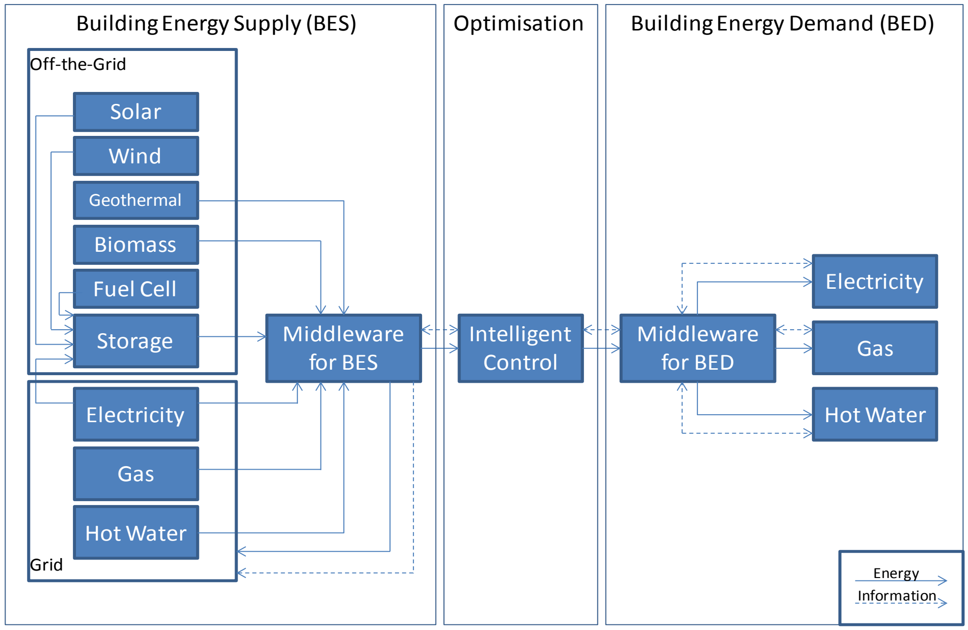

Figure 1: A smart building concept integrated with off-the-grid energy generation systems.

3. CONCEPT

At present, off the grid energy generation technologies are usually provided by the companies which solely focus on specific areas such as wind, solar, geothermal, biomass and storage as there is a very limited number of companies that provide a "total service concept". Therefore, holistic design between various energy generation systems hasn't been provided in an expected granularity due to the lack of integration concepts.

Moreover, the control of energy performance of buildings is often provided by an ad-hoc combination of off-the-shelf building management components, distributed data metering equipment, glued together by M&T software tools. The absence of building management systems standardization coupled with competition for market share results in independent and non-compatible system development. In this regard BACnetTM was developed to provide an open, non-proprietary protocol specification that allows building automation controllers of different manufacturers to communicate with each other (ASHRAE 2003). However Building Management Systems / Energy Management Systems still operate on non-standardized proprietary interfaces. Consequently they are becoming more complex over time and are difficult for the average operator to understand given the educational and experience (Lowry 2002). Additional training overhead is required for each new system or system updates. Moreover (Hatley et al. 2005) states that in the absence of compatible hardware and communication protocols maintenance can become extremely problematic as seamlessly integrating these systems is an inefficient overhead.

However, in conjunction with traditional procurement policy it is conceivable that numerous systems which would provide an integrated system chain enabling the efficient use of renewable energy resources and energy management systems in a holistic building-supply and building-demand side energy management concept complementing with a modular approach should appear, as can be seen in this research.

In this regard three research concepts are provided by defining: (1) Integration and optimisation of off-the-grid energy generation systems. (2) Multi dimensional information management platform backed by data warehouse technologies and wireless embedded systems. (3) Intelligent control module for low energy building operations.

3.1 Integration and optimization of off-the-grid energy generation systems

Integration and optimisation of off-the-grid energy generation systems involves two complementing phases (1) the design of small scale house type renewable energy technologies e.g. wind, solar, geothermal and storage systems for off-the-grid energy generation and storage in buildings through an integrated structure based on the requirements analysis including energy demand and grid supply patterns and (2) the development of an optimisation middleware for energy-supply, in order to control the various systems in an integrated and optimized way.

3.1.1 Off-the-grid energy generation and storage systems

Off-the-grid renewable energy technologies for energy generation for buildings usually addresses individual systems integration, e.g. a wind turbine is combined with adequate storage devices or energy harvesting facades are combined with actuators or blind control systems. Several tools supporting the integration of these components exist with manufacturers having usually their own preferences.

Therefore the definition of optimal processes and interfaces allowing the integration of different systems e.g. integration of small scale battery charging wind turbines and photo-voltaic solar cells which feed a common storage system (battery bank) and control of energy production on the basis of environmental conditions e.g. wind speed, day light period, etc. can be accepted as one of the prerequisites of a holistic, modular approach.

In this research, in order to integrate different type of systems in an optimized way, the requirement and the state-of-the art analysis which would allow optimized integrations have been obtained with researching the systems given below. This preliminary state-of-the art analysis will be used to develop the middleware for building energy supply.

3.1.1.1 Small scale battery charging wind turbines

After examining, different type of home use small scale wind turbines in the market, 600W 24VDC battery charging wind turbine with 6 Blade type has been chosen to optimise small scale renewable energy output which is compatible with our application scenarios. Its cut-in speed is low in order to facilitate continuous generation and auxiliary energy source. The wind speeds in excess of 150km/h has been approved. This type of home use wind turbines generally comprises of a single axial flux permanent magnet brushless alternator. The six blade design supports a self-regulating aerodynamic rotor that achieves speed control through blade turbulence, which controls the speed of the rotor with no moving parts and no obtrusive noise. The diameter is 1.5m.

3.1.1.2 Solar Panels made of photo-voltaic solar cells

In this research, 4 major types of Solar Technology Panels have been examined (1) polycrystalline cells which are the most common and cheapest panels with conversion efficiency 13% to 15% (sunlight to electricity), however, under elevated temperatures of 50 degrees Celsius panel temperature, the efficiency drops by around 20%, (2) panels made from monocrystalline cells which are used in high reliability applications such as telecommunications and remote power with conversion efficiency is typically 14-17.5% (higher than the polycrystalline cells), however, at elevated temperatures, the efficiency only drops by 10-15% so they are more consistent in output (3) Panels made from amorphous cells which have been used in portable items for many years with conversion efficiency of sunlight to electricity is 5-7%, about half that of the other panels but unlike the other types, their output does not decrease in elevated temperatures. Panels made of thin film cell CIGS technology (Copper, Indium, Gallium, diSelenide) are flexible, durable, and provide slightly higher efficiency than other flexible solar cells, typical sizes less than 60W and can be mounted to curved surfaces. The critical item that delivers the current to charge the batteries is the solar controller. There are 3 major types of controller: (1) Standard single phase controller, (2) Multistage controller, and (3) Maximum Power Point Tracking Controller (MPPT). The first 2 controllers provide roughly 70% of the panels power to the batteries as they reduce the voltage of the solar panels but do not increase the current. MPPT Controllers are true “State of the Art” technology with 96%+ output. The final critical factor is the location of the controller, the mounting the controller at the battery end of the solar panel cable allows batteries fully charged. In summary, the way to compare the relative output capacity of panels is by the current output charging batteries at around 13.5V.

In our case with considering the current systems, the high quality polycrystalline solar panels for home solar power systems and MPPT controllers are used in this research.

3.1.1.3 Solar vacuum-tube collectors for hot water

In order to heat water using solar energy, a collector, often fastened to a roof or a wall facing the sun, heats working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. Residential solar thermal installations fall into two groups: passive and active systems. Both typically include an auxiliary energy source (electric heating element or connection to a gas or fuel oil central heating system) that is activated when the water in the tank falls below a minimum temperature setting such as 55 ℃. Hence, hot water is always available. The combination of solar water heating and using the back-up heat from a wood stove chimney to heat water can enable a hot water system to work all year round in cooler climates, without the supplemental heat requirement of a solar water heating system being met with fossil fuels or electricity. For this research Viessmann Vitosol 300 T type SP 3A Vacuum-tube solar collectors with dry connection heat tubes have been chosen. The system has gross area of 2.88 m^2 and the absorber area of 2.00 m^2 .

3.1.1.4 Geothermal heat pumps

A geothermal heat pump, ground source heat pump (GSHP), or ground heat pump is a central heating and/or cooling system that pumps heat to or from the ground. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). In a fridge, heat is transferred from the inside to the outside. With a heat pump, this happens exactly the other way round. Heat from the air or the ground is transferred into the living space via the heating system. Vapour from a refrigerant is compressed to increase the temperature, to make it high enough for central heating and DHW (Domestic Hot Water) heating. For this research, the selected Viessmann Vitocal 350-G reaches up to 72 ℃. These heat pumps can therefore also be used for modernisation as they can provide a sufficiently high flow temperature for central heating with radiators. The compression process is vital for the efficiency of a heat pump. To generate heat, for example, heat is extracted from the ambient air and used to evaporate a refrigerant that boils at low temperature. Getting hotter towards the centre – from an initial temperature of between 5 and 18 ℃, a flow temperature of up to 72 ℃ is achieved. The gas created is compressed by the scroll compressor, which causes it to heat up. The gas heated in this way transfers its heat via the condenser to the heating water or DHW heating system, and thereby condenses again. Finally, the refrigerant, which is still under pressure, is expanded in an expansion valve, and the circuit begins again. A heat pump can make use of the following energy sources: (a) Air – practically unlimited availability; lowest investment costs (b) Ground – via geothermal collector or geothermal probe. (c)Water – efficiency depends on the water temperature. (d) Waste heat – subject to availability, volume and temperature level of the waste heat. In this regard, the best heat source for each individual case depends on local conditions and the actual heat demand.

3.1.1.5 Fuel cell system

A fuel cell is an electrochemical energy conversion device. A fuel cell converts the chemicals hydrogen and oxygen into water, and in the process it produces electricity. Fuel cells generate electrical power quietly and efficiently, without pollution. Unlike power sources that use fossil fuels, the by-products from an operating fuel cell are heat and water. A fuel cell provides a DC (direct current) voltage that can be used to power motors, lights or any number of electrical appliances.

In this research, polymer electrolyte membrane fuel cells (PEMFC) are used. The PEMFC has a high power density and a relatively low operating temperature (ranging from 60 to 80 degrees Celsius, or 140 to 176 degrees Fahrenheit). The low operating temperature means that it doesn't take very long for the fuel cell to warm up and begin generating electricity.

The specific system solution is Serenergy H3 5000 Methanol Power System (Serenergy 2013). The system is Methanol fuelled – integrated reformer system Liquid cooled High Temperature PEM stack with 5 kW electrical power output. The H3 5000 Methanol Power system can be used to supply an onsite, external battery pack existing on site or installed with the system. The methanol fuel cell system is ideal for combining with renewable energy sources such as wind and solar or multiple applications, both off- and on-grid, including application in critical backup power, temporary power or premium power generation.

3.1.1.6 Energy storage systems

For energy storage systems two types of batteries have been examined, (1) Lead Acid Deep Cycle Batteries which are designed to have stored current discharged between charging sessions, with very heavy non-porous battery plates to withstand repeated major discharging and charging cycles (deep cycles) and (2) Nickel Alloy Batteries Nickel Cadmium (NiCad) and Nickel Iron batteries, rather than consisting of lead plates submerged in a sulfuric acid solution, feature nickel alloy plates in an alkaline solution.

In this research, we have chosen nickel alloy battery types for our experiments with considering the facts such as they are well suited for home power use, although much less common and much more expensive than lead acid types. The nickel alloy battery can have up to 50 years of useful life, compared to 20 years with a well-maintained lead acid battery. They can also sit for extended periods of time partially or fully discharged without suffering damage, unlike lead acid types and they need lower maintenance. On the other hand a lead acid battery should never be completely discharged, meaning they need to be more closely monitored. Nickel alloy batteries operate better at lower temperatures, and can discharge more of their total amp-hour capacity as useful current.

A battery bank is the main part of the energy storage systems and enables a constant level of power to the house. Without the battery bank, the entire electrical system of a house would be limited by the immediate output of renewable energy resources. A wind turbine would be subject to constant power fluctuations as the wind speed increased, dropped or disappeared entirely. At night, a solar-run house would have no electrical power available. Therefore in order to provide a constant level of power without causing problems for households, a grid connection to the battery banks would be necessary during non-peak hours, thereby the house-use power can be available regardless of weather conditions with convenient electricity prices.

In our case, we designed our system based on three separate battery sections composed of nickel alloy batteries. The first section is connected with the small scale battery charging wind turbine, the second section is connected with the high quality polycrystalline solar panel while the third section connected to the central electricity grid. Therefore the wind generator and solar panel can deliver power to the battery bank regardless of current power usage, so excess power can be stored during low use times (generally the middle of the day and middle of the night) and be available during high use times (usually morning and evening). In our case an inventer DC-AC which is used to convert the DC power from the battery bank to AC power for the house power systems, a rectifier AC-DC which converts AC grid power to DC power for the use of battery charging, a control relay which provides a direct connection between the house and the grid in the event that all stored energy is depleted or a problem occurs in the battery bank.

3.1.2 Middleware for building energy supply systems

This is considered for the integration of off-the-grid power generation systems and central electricity/gas grid and optimal control of these systems on the basis of occupant needs and environmental factors. In order to provide this, a novel model-based system development approach is investigated that automates code development. In the model-based system development approach, we propose to adopt the software product line paradigm. It starts with requirement engineering for the envisaged systems specifying the functionality to be implemented. From these requirements the source codes are individually generated from software modules to fulfil the requirements and optimally use the system resources. Information about the implemented functions, requirements, and software function blocks are stored in the form of Electronic System Descriptions. This repository contains descriptions of individual systems for integration purposes. Consequently on the basis of specified descriptions which allow controlling of optimal management of wind turbines, solar panels, geothermal systems etc. The middleware is designed with considering the functionalities given below.

The middleware is in control of charging the batteries when out of power from either the grid or renewable energy systems occurred. It will supply the hot water by taking into consideration of the occupant requirements and environmental factors. The middleware also be in control of providing stored power to the house whenever possible. It is designed for running the system in the most cost effective manner by considering carbon emissions.

It would decide when to charge the batteries and from which source. The middleware is designed to provide stored power to the house whenever present and only switch to grid power if all stored power is depleted.

Moreover it provides charging the batteries from the grid power during non-peak hours and only if the systems could not provide enough power for the house use.

3.2 Multi dimensional information management platform backed by wireless embedded systems and data warehouse technology.

Multi dimensional information management platform is implemented on the basis of three complementing phases as (1) Development of Building Information Model, (2) development of wireless sensor network platform, (3) development of data warehouse system.

3.2.1 Development of building information model (BIM)

In order to simplify the requirement engineering, information about the building (location, building systems, etc.) can be imported from the systems which support architectural and building systems design. Architectural designs are typically developed with the Computer Aided Design (CAD) tools such as Autodesk Revit, Microstation, ArchiCAD and DDS-CAD. They support standardised, extensible Building Information Models (BIM) based on product modelling standards such as IFC (Industrial Foundation Classes).

The concept of a BIM describes an integrated data model that stores all information relevant to a building throughout the building life cycle. In our case, it is envisioned to extend the BIM with the system design, e.g. the number and kind of wireless sensors and communication devices in order represent deployment in different rooms and their interaction within each other and with the building itself.

In order to predict and model building energy performance, energy simulation models should be considered. These models enable the building operator to perform comparisons between design intent and actual energy performance data. For example, in order to perform an energy simulation on the Revit MEP model, the IES plug-in is used in our simulations to complete BIM Model comprising energy performance aspect.

3.2.2 Development of wireless sensor network platform

Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors that allow the physical environment to be monitored at high resolution. These sensors also called motes are installed in particular locations or can be deployed in a particular zone to gather information such as temperature, humidity, CO2, lux level, etc. The real functionality of sensors comes with wireless sensor networks when these sensors start communicating with each other through wireless protocols. WSN can shuffle the information collected through the sensors and transfer it to the public internet and or a local area network. Finally, the information is collected in the data warehouse where it is analysed.

In this project the wireless sensor network architecture is implemented based on the recently released IETF 6LoWPAN (RFC 4944) open standard for IP communication over low-power radio links – IEEE 802.15.4 represents one such link. WSN LoWPAN networks are connected to other IP networks through one or more border routers forwarding packets between different media including Ethernet, Wi-Fi or GPRS. The IP architecture offers widespread commercial adoption and broad interoperability due to its attributes such as openness, flexibility, scalability and manageability. Many industrial standards, including BACNet, LonTalk, CIP and SCADA, introduced an IP using either TCP/IP or UDP/IP over Ethernet.

In this research the wireless sensors have been chosen to detect and measure various parameters such as temperature, humidity and water/gas/electricity meter readings. In our case the motes, mainly consists of 3 components; the sensor interface which actually measures the physical attributes like humidity level, the radio interface which communicates with other motes and the CPU which performs computations and transfers information between the two components. The used board is equipped with an Atmega1281 MCU and EM2420 radio chip. The platform includes sensors for monitoring air-temperature, air-humidity and light. Moreover incorporates electricity meters as well as the interface for controlling (on/off) an AC load are utilised. The platform runs the recently released b6LoWPAN stack. Soekris embedded PC boards (Soekris 2012) with Atheros CM9 Wi-Fi cards and a single IEEE802.15.4 node form a backbone network will be used in all the rooms of the sample building.

3.2.3 Development of data warehouse system

The objective of the data warehouse development is to provide a multi dimensional information management platform to store integrate and analyse complex data sets from multiple information sources such as model editors, energy simulation tools and performance framework specification tools as well as data streams collected from wired and wireless sensors and meters in order to analyse building performance data and to support decision making process of the stakeholders. The developed system is explained in detail by (Gökçe 2010,2011,2012).

3.3 Intelligent control module for low energy building operation

The middleware for energy supply and data warehouse technologies are integrated within the intelligent control module for low energy building operation in order to control and optimise both building energy supply side and building energy demand side in run time.

The intelligent control module contains algorithms for the defined building operation scenarios (e.g. heating, cooling, and lighting) and interacts with the data warehouse core to compute control parameters, which are then passed to the wireless network for actuation. The detailed description of the intelligent control module has been provided by (Gökçe 2011, 2012).

4. CONCLUSIONS

In this paper an integrated building energy management system composed of (1) Building energy supply-side and (2) Building energy demand-side management is described. The proposed concept integrates energy production systems from renewable energy sources, building energy diagnostics and predictive control, ubiquitous wireless sensing technologies, and micro-grid power electronics and power control. The research focuses on an innovative model-driven development approach that integrates systems in building energy supply-side and building energy demand-side to provide optimized energy production/consumption. The research findings will be demonstrated in an appropriately selected office building in Hannover, Germany integrating different energy efficient production/consumption systems addressing the renewable energy technologies, energy storage systems and building energy management systems comprising scalable and robust sensing network platforms, energy performance monitoring and data mining technologies. The initial research findings will be used to extend this research to the smart cities level.

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