A review of prefabricated self-sufficient facades with integrated decentralised HVAC and renewable energy generation and storage

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Abstract

To be future proof, it is essential for buildings and their heating, ventilation and air-conditioning (HVAC) systems to be adaptive to changing climate and occupancy scenarios and supplied with locally generated renewable energy. To accomplish this, the trend is towards decentralising HVAC and energy-generating equipment into prefabricated non load-bearing facade systems, which can be replaced with minimal disturbance to the building core and its ongoing activities. Key to a successful implementation of such facades in the building industry, is self-sufficiency through facade-integrated energy storage and the absence of (grid/water) supply and drainage lines. This review discusses the savings potential of about 50 facade systems and projects classifying them according to their renewable energy generation, storage and HVAC technology. Up to 63 kg/m^2a CO_2-equivalent savings have been reported for the considered technologies. Although many studies are energy-neutral, few attempts towards self-sufficient facade-integrated storage are published. Decentralized ventilation combined with thermo-electric elements or air-to-air heat pumps further shows potential for self-sufficient curtain wall-integrated HVAC. This review, however, found no self-sufficient prefabricated facade system on the market with integrated HVAC.

Keywords: self-sufficient, building facade, curtain-wall, HVAC, thermo-electric, renewable, energy, battery

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1. Introduction

By 2050, current projections suggest that population growth and urbanisation will generate a two- to three-fold rise in global energy use for the building sector, with a similar impact on associated emissions [30, 66, 68]. Renewable sources contributed more than 40% to Germany's public net electricity generation in 2018, with solar energy showing the largest growth [14]. Photovoltaic (PV) electricity, for example,

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has recently become the lowest cost source of electricity in most parts of the world [50]. Furthermore, urbanisation combined with rising land prices and land scarcity in cities leads to buildings with a high facade-to-roof ratio [47]. Due to the weight of such high-rise buildings, non-load-bearing light-weight prefabricated (prefab) curtain wall glass facades, with a high convection coefficient instead of construction materials that cause higher thermal energy loss, have become increasingly common [92]. Especially in high-rise buildings, facade-integrated (FI) renewables such as building integrated photovoltaics (BIPV) can be a viable alternative to roof-mounted or distant energy-generation, and contribute significantly in the struggle against climate change [38]. Worldwide, the achievable ratio FI electricity production potential / current electricity consumption varies from 5.8 to 23.2% if all architecturally suitable facade areas are used, depending on the country, assuming an average building proportion (high- vs. low-rise), floor area/capita, geographical solar irradiation, and shading for each country [1]. Combining facade with roof PV, these numbers are respectively 30 to 120% [1]. Hence, as several lighthouse projects show [2, 64, 132], in countries such as the USA, BIPV could cover the entire building energy demand to create energy-neutral buildings. Nevertheless, despite the potential, BIPV represents only about 3% of all solar installed capacity in the EU [35]. Renewable energy storage (RES) is key for incorporating renewables into a secure EU grid [114]. It can reduce generation-load imbalances and assist in primary frequency regulation. The use of BIPV with batteries, for example, as demonstrated by a few lighthouse projects [2, 11, 64, 132], has been advocated for increased operational flexibility and resiliency of building renewable energy generation (REG) [29, 31, 62, 63, 73], and can, under the right circumstances, be economically feasible [111]. Besides generating electrical and thermal energy, FI REG sources have been documented to contribute to shading [77] and to building thermal insulation [18, 24, 131].

The material requirement of buildings currently represents one of the greatest resource use challenges in terms of mass of resources used, as more than 30-50%[1] of total material use in Europe goes to housing [113]. As currently only about 50% of total waste gets recycled [36], increasing the building life-span could significantly reduce the burden on waste production and resource depletion. Research shows that there is no significant relationship between the structural system (material) and the actual useful life of the building [97]. Reasons for building demolition are instead related to lack of suitability of the building for current needs and lack of maintenance of various non-structural components. To increase the building life-span flexibility and changeability, with regard to future occupancy, technology and climatic conditions, are key.

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[1] different sources give different numbers

Concentrating the building elements with shorter lifetime, i.e. the HVAC, REG and facade system, separate from the building core structure greatly improves the ease of technical upgrades with minimum building disruption and increases the chances of building renovations as compared to building demolition. In the last two decades, various buildings with FI HVAC arose (see Table 1 B1-B16), and various studies of facade systems with in-built HVAC, REG or RES systems have been published [17, 32, 45, 65, 71, 82, 85, 86, 122, 130] (F1-F29), that contribute in that respect. Development of these designs into market-ready products and a widespread implementation of these systems in buildings has so far been hammed by complications in the planning and in execution at the construction site, amongst others caused by connections of electricity cables, water pipes and condensate drains from the facade to the building core. Communication between stakeholders, the lack of flexibility within the production and supply chain and process related barriers are furthermore amongst the main perceived barriers for the development of facades with integrated building services [103]. Modular prefab non-load-bearing light-weight facade systems, such as curtain walls, with integrated REG and storage systems and decentralised HVAC, could overcome this barrier and enable a quick and easy supply and application. If those facade systems are self-sufficient, they can eliminate the need for communication between different building trades as well as the need for cables and pipe-works to the building core altogether, and thereby increase the changeability with reduced disturbance to the ongoing activities within the building core.

2. Methodology

This review compares the self-sufficiency-level of state-of-the-art prefab facade systems with in-built HVAC, REG and RES systems. Decentralized HVAC in this review is defined as a FI system with air supply through facade openings and FI air treatment (heating, cooling, heat recovery, etc.) meeting the criteria as per [119]. REG are defined as FI technologies that provide electrical (by means of PV or wind energy), thermal (i.e. solar thermal (ST)) or thermochemical (i.e. bioreactors) energy that can aid the facade or adjacent room on top of conventional passive thermal transmission through the facade. Electrical and active thermal or thermochemical FI RES techniques are reviewed if they can contribute directly to the facade's energy consumption or HVAC. Hence, passive RES such as (phase change materials as part of) the thermal building mass are not part of this study. The selected studies are further reviewed to the level of self-sufficiency beyond energy-neutral by incorporating appropriate RES, in other words to what extent the facade systems can function as standalone building elements that can operate independent of and without supply connections to the building core, i.e. the absence of a grid (energetic self-sufficiency), water, liquid or other connections (water/liquid self-sufficiency).

An overview of the studies reviewed is presented in Table 1 and further referred to with serial numbers Fx and Bx. To put the energy savings of the various studies in perspective, we have converted them without corrections to CO_2-equivalents. These can, however, not be taken as absolute values since the basis and reference assumptions for the studies reviewed vary. The studies reviewed are selected from English and German scientific publications with keywords; facade, building envelope, building shell, self-sufficient, renewable, energy generation, energy storage, and HVAC. There is no restriction to the year of publication. The review is confined to prefab facades that are assembled off-site, since cable and pipe connections of such facades to the building core provide bigger constraints that involve multiple contractors. Facade types typical for high-rise buildings, such as curtain wall systems, precast concrete walls, in particular those light-weight with thickness up to 300mm (thin facades) such as unitized curtain walls, are of upmost interest in this review, considering the land scarcity in cities. As this review focuses on the market-availability of facade systems, only studies that involve a prototype or have reached an implementation stage are considered, thus excluding only theoretical studies. Facade systems and projects considered need to further generate renewable energy. In addition to that they need to be over 70% energy-neutral, store the generated energy locally, or have a FI HVAC or dynamic shading and daylight distribution system. Facade systems that provide an architectural facade appearance that aims to overcome the barrier to facade use acceptability are of particular interest in this review, since the lack of design is considered one of the main reasons of the slow spread of FI REG like solar thermals [59, 79, 90, 106]. This implies that for FI REG technologies that have been researched broadly such as solar thermal REG, e.g. those studies that aim to avoid the visibility of piping or absorber irregularities are selected. The novelty of the work lies in a thorough research of facade systems comparing their level of CO_2-reduction and self-sufficiency from the point of FI REG, RES (FI batteries and storage tanks) and consumption (FI HVAC) and from the point of required drainage and supply connections to the building core. This review therefore provides new insight into the state-of-the-art and feasibility of complete self-sufficiency of prefab facades with integrated HVAC.

3. Facade-integrated renewable energy systems (REG)

REG technologies suitable for facade integration include solar electric (PV, thermo-electric), solar thermal (water, air, sorption, desiccant), thermochemical (microalgae) and wind-energy systems. Most of the

Table 1: Reviewed studies of facades with integrated renewable energy generation, storage or HVAC system

S.No.	name	location	building[12]/facade type	facade-integrated renewable energy[3]	electrical / thermal saving	CO_2-eq.[4] kg/m^{2}a	integrated thermal/ electrical storage	(facade-) integrated decentralised HVAC[6]	supply/drain connection
F1	BPPL [76]	Seattle, USA	curtain wall	PV wedged, elec.	covers demand, 137 MWh/a electricity	34	lithium-ion 84kWh	no	no
F2	RenoZEB smart-IoT [7]	Bilbao, Spain	(double-skin) curtain wall	PV elec.	63% of 40 W/m^2 cooling load [53], 50% PV	9	small battery	dynamic shading & daylighting	no
F3	TEmotion [122, 124]	Germany	(unitized) curtain wall	PV cool/heat	self-sufficient, 40-50% electrical, 37W/m^2 PV	8	no	liquid-based HVAC, heat recovery	grid, water
F4	Adaptive Solarfassade [91]	Zürich, Switzerland	curtain wall	PV elec.	86kWh electrical, 38kWh demand savings	19	no	dynamic shading & daylighting	grid
F5	Sunthink [54, 61]	München, Germany	curtain wall	PV elec.	100 kWh/m^{2}a electrical	22	no	dynamic shading & daylighting	grid
F6	CoolSkin [32]	Vienna, Austria	(unitized) curtain wall	PV cooling	covers demand, 2130 Wp, 0.85 kW cool	32[11]	2 LiFePO4/1152Wh	HP (COP 4), AC, water cooling, MV	water, drain
F7	HVACviaFACADE [71, 120]	Graz, Austria	curtain wall	PV heating	up to 70% from 30 kWh/m^{2}a heat	14[11]	ext. DHW storage + thermal	HP air, water (COP 2) & MV	grid, water
F8	SaLüH [94]	Innsbrück, Germany	prefabricated timber	PV heating	up to 24% from 5800 kWh/a*flat	26[11]	ext. battery	HP air-to-air (COP 2.7) & MV	grid, drain
F9	Facade CTU Prague [86]	Prague, Czech	curtain wall	PV cool/heat	covers demand, 86/96/33 W el./heat/cool	1/2[11]	flat battery	TEHCE (COP 0.68/2.2), MV	drain
F10	Thermal active manifold [45]	Indiana, USA	double-skin, manifold	PV cooling	85 W electrical, 72 W cooling	6[11]	no	TEHCE (COP 0.3), MV	grid, drain
F11	Active building envelope [129, 130]	New York, USA	window-system	PV cool/heat	40 W/module el., 51 W heat, 18 W cool	3[11]/9	water thermal storage	TEHCE, water pipes	grid, water
F12	Solar cooling facade [82, 83]	Changsha, China	rear-ventilated opaque	PV cooling	PV 18 W/m^2, 9.7 + 13.3 W/m^2 thermal	4[11]	no	TEHCE, MV, radiant heat panel	grid, drain
F13	BRESAER [3, 16]	Athens, Prague	prefabricated retrofit	PVT heating	40 – 70 % i.e. ca. 45 kWh/m^{2}a	22	no	solar thermal air heating	grid
F14	Thermo-electric Peltier [65]	Navarra, Spain	rear-ventilated opaque	ST air cool/heat	1000 W thermal output / 20 Peltier cells	-/24	no	TEHCE, MV	grid, drain
F15	Solar cooling facade [17]	Delft, Netherlands	curtain wall	ST air cooling	1 kW/0.52 kW, (13.2 W/m^2) thermal	2[11]	water thermal storage	TEHCE, ventilation (COP 1.92)	grid, water
F16	SolarWall® [4, 5]	France	micro-perforated metal	ST air heating	300kWh/m^{2}a thermal	55	no	solar thermal air heating	no
F17	Solar-thermal desiccant [39]	Malaga, Spain	rear-ventilated opaque	ST air cooling	removes 30 W/m^2 latent load	5[9]	no	desiccant dehumidifier, MV	no
F18	iNSPiRe 2016 [9, 10, 23]	Stockholm, Rome	curtain wall	ST VT cooling	15 – 40% cooling, 60 kWh/m^{2}a	11	(ab)sorption storage	MV, elec. heating/cooling coil	grid
F19	WICTEC CPC [123, 125]	Bellenberg/Stuttgart	(unitized) curtain wall	ST VT heating	178kWh/m^{2}a [49]	32[7]	no	dynamic shading & daylighting (HC)	grid, water
F20	Solar blinds Arkol [27, 42]	Germany	curtain wall	ST HP heating	178kWh/m^{2}a [49]	32[7]	no	dynamic shading & daylighting (HC)	grid, water
F21	Strip collector Arkol [27, 43]	Germany	rear-ventilated, plaster	ST HP heating	178kWh/m^{2}a [49]	32[7]	no	(HC)	grid, water[8]
F22	iNSPiRe 2018 [10, 13, 23]	Stockholm, Rome	curtain wall	ST fluid	-	-	water thermal storage	radiator	grid, water
F23	SOLABS [107, 133]	Lausanne, Switzerland	unglazed steel absorber	ST fluid	-	-	no	(HC)	grid, water[8]
F24	Solar-thermal Giovanardi [46]	Rome	unglazed absorber	ST fluid heating	62.5% efficiency	63	water thermal storage	(HC)	grid, water
F25	TABSOLAR [27, 44]	Germany	ETICS, rear-ventilated[1]	ST fluid heating	266 W/m^2 [70]	47	ext. 390 L ice-storage	solar thermal fluid heating radiator	fluid
F26	EWICON [22, 26, 87]	urban environment	(double-skin) curtain wall	Wind-energy	1.5 % efficiency, 2.3W/m^2 10m/s [93]	4	ext. battery	no	grid
F27	AerovoltaicTM [108]	urban environment	(double-skin) curtain wall	Wind-energy	10W/m^2, forecast 100W/m^2 [93]	19	ext. battery possibility	no	grid
F28	Algae facade [77]	Washington DC	curtain wall	Photobioreactor	0.15L/m^{2}a biofuel + 9 kg/m^{2}a CO_2 absorption[10]	50	ext. thermal storage	(HC)	grid, water
F29	SolarLeaf blinds [19, 20]	Munich, Germany	(double-skin) curtain wall	Photobioreactor	30/150 kWh/m^{2}a biomass/thermal	55	ext. thermal storage	(HC)	grid, water
B1	Capricorn (205) [128]	Düsseldorf, Germany	o/(unitized) curtain wall	no	14.7 kWh/m^{2}a reduced vent. loss [85]	4	no	VAV sup.-ret. parapet (HP cca)	grid, water
B2	Obsidian (201) [60]	Zürich, Switzerland	o/(double-skin) curtain wall	no	375 kWh/m^{2}a energy consumption [85]	-5[2]	no	CAV sup. u.floor, cen. ret. (HP cca)	grid, water
B3	Zürich 2002 (203) [84]	Zürich, Switzerland	o/perforated, concrete[1]	no	170 kWh/m^{2}a energy consumption [85]	39[2]	no	pas. sup. parapet, cen. ret. (HP cca)	grid, water
B4	Neckarsulm 2006 (202) [84]	Neckarsulm, Germany	o/ribbon window facade	no	318 kWh/m^{2}a energy consumption [85]	7[2]	no	VAV sup. u.floor, cen. ret. (DHCC cca)	grid, water
B5	Hallesche, Reinsburgstr. 10 (204) [85]	Stuttgart, Germany	o/perforated facade	no	458 kWh/m^{2}a energy consumption [85]	-23[2]	no	VAV sup.-ret. parapet (DHCC)	grid, water
B6	Freiburg 2006 (207) [84]	Freiburg, Germany	(double-skin) curtain wall	no	267 kWh/m^{2}a energy consumption [85]	18[2]	no	VAV sup. u.floor, cen. ret. (HP cca)	grid, water
B7	Konzernzentrale Bayer (008) [12]	Leverkusen, Germany	(double-skin) curtain wall	no	314 kWh/m^{2}a energy consumption [85]	8[2]	no	pas. sup. u.floor, cen. ret. (cca)	grid, water
B8	Study by Uni Stuttgart [37]	Stuttgart, Germany	curtain wall	no	13 kWh/m^{2}a saving	3	no	VAV sup.-ret. u.floor	grid, water
B9	German history museum (206) [121]	Berlin, Germany	m/historical perforated facade	no	unknown (heating via DHCC)	-	no	VAV sup. parapet, cen. ret. (DHCC)	grid, water
B10	Laimer Würfel (209) [56, 85]	München, Germany	o/perforated facade	no	unknown (heating via DHCC)	-	no	VAV sup.-ret. parapet (DHCC)	grid, water
B11	Neumühlen 19 (110) [99]	Hamburg, Germany	o/(double-skin) curtain wall	no	unknown	-	no	pas. sup. u.floor, cen. ret. (HP)	grid, water
B12	Post Tower [57]	Bonn, Germany	o/(double-skin) curtain wall	no	unknown	-	no	VAV sup. u.floor, cen. ret. (cca)	grid, water
B13	Feldbergstraße 35 [80]	Frankfurt, Germany	o/curtain wall	no	unknown	-	no	VAV sup.-ret. parapet	grid, water
B14	Imtech Haus [80, 88]	Hamburg, Germany	o/curtain wall	no	unknown	-	no	VAV sup.-ret. parapet	grid, water
B15	Light Tower [80]	Frankfurt, Germany	o/curtain wall	no	unknown	-	no	VAV sup.-ret. parapet	grid, water
B16	Office Rue Guersant [96]	Paris, France	o/curtain wall	no	unknown	-	no	VAV sup.-ret.	grid, water
B17	ABB multi-family [64, 110, 112]	Brütten, Switzerland	mr apartment/brick	PV facade, roof	fully covers the demand	4-20	ext. thermal + electrical	no	no (off-grid)
B18	NeighborHub solar [21, 132]	Denver, USA	d/double-skin glass	PV facade	fully covers the demand	38	ext. lithium-ion 10.8 kWh	no	grid
B19	KfW efficiency 40 plus [64]	Wilhelmshaven (G)	d/brick	PVT balcony, roof	covers 70% of the demand	9	ext. thermal + 44 kWh[5]	no	grid for 30%
B20	Alstonvale net zero house [15]	Hudson, Canada	d/PV-in-roof	PVT roof vac. tube	covers 70% of the demand	71	ext. thermal storage	(solar thermal air heating)	grid

[1] ETICS: External Thermal Insulation Composite Systems, prefabricated (prefab) concrete facades such as double or sandwich-walls

[2] Savings are compared with the EVA average of 350 kWh/m^{2}a [85] p.35 for total energy consumption. Savings are not solely caused by the decentralised HVAC. m^2 refers to floor area

[3] PVT: PV combined with solar thermal, ST: solar-thermal, VT: Vacuum tube, HP: heat-pipe

[4] CO_2-equivalents are calculated using conversion factors; 0.215 kg CO_2/kWh electricity [74], 0.18 kg CO_2/kWh solar thermal, 0.35 kg CO_2/kWh biogas, 0.3 kg CO_2/kWh biomass [19], CO_2 Biodiesel 2661 g/gallon, petroleum diesel fuel 12,360 g/gallon [28]

[4] m^2 refers to (renewable energy generating) facade area. a 1:1 ratio of floor to facade is assumed

[4] Unless other data was provided by the respective studies, the following assumptions were made: reference facade with zero renewable energy generation, Munich climate 550 kWh/m^{2}a global radiation on vertical surfaces [19], 980 solar hours/a [69]

[5] lithium ion phosphate batteries and used to turn water into hydrogen fuel

[6] TEHCE: Thermo-electric heating/cooling elements, CAV: constant air volume, VAV: variable air volume, pas.: passive, act.: active, sup.: supply, ret.: return, u.floor: underfloor, cen.: centralised, MV: mechanical ventilation

[6] HC: heating/cooling, cca: concrete core activation of floor/ceiling, HP: heat pump, DHCC: District Heating Compression Chiller, (not facade-integrated items in brackets)

[7] Since limited data is available for this product, reference performance data for a similar product tested in Munich is used to calculate the CO_2-equivalent.

[8] This study has been selected, despite the absence of storage and HVAC, because of the flexible, (on-site) re-sizing of the prefabricated system (dry thermal connection).

[9] kg/ma

[10] Since [77] did not document the thermal energy generation of the algae facade, the thermal energy savings (150 kWh/m^{2}a) were based on those documented in [19].

[11] For calculating the CO_2 savings for this cooling/heating systems, the output capacity has been used, to include the benefit of higher COP systems.

[12] O: office, m: museum, mr: medium-rise, d: dwelling

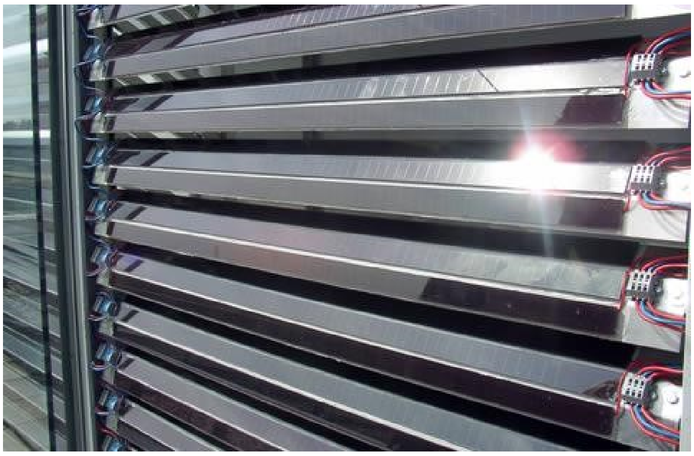
Figure 1: Sunthink photovoltaic-blinds [61]


Figure 2: ASF PV-module at HoNR ETH Zürich [33]

facade systems with integrated REG systems analysed use BIPV as the primary source of energy [3, 76, 86, 100, 122] (F1-F13). They range from fixed to flexible sun-tracing PV. The *'Sunthink'* PV sun protection slat with thin-film solar cells can generate $100kWh/m^2a$ (Figure 1) [54, 61] (F5). With the Adaptive Solar Facade (*'ASF'*) [91] (F4) (Figure 2) currently in the test phase, each individual thin-film module can be individually controlled by tracking the position of the sun and move independently of the others [34, 81]. Simulation results, compared to a glass facade without shading, indicate 25-56% energy and 11% heating savings and conclude that the *'ASF'* should be installed on buildings with a high cooling load, whereas an equivalent static PV sun protection is more beneficial on buildings with a high heating load [72].

Solar thermal (ST) energy is another prominent source of REG [3] (F13-F25). The advantage of FI ST systems is the generation during demand due to low sun angles in winters on facades. For 20 years, the micro-perforated metal collector *'SolarWall®'* with 80% solar efficiency (Figure 3) has generated up to $600W/m^2$ of thermal energy in preheated fresh air, while heating costs were reduced by up to 50% [4, 5] (F16). As part of the *'TABSOLAR'* project with Fraunhofer ISE, solar absorbers and thermally active, flow-through components made of ultra-high-strength concrete (UHPC) were developed for use in ventilated facade systems, composite thermal insulation systems or prefab concrete walls (Figure 4) [27, 58] (F25). The unglazed solar absorber *'SOLABS'* for building facades consists of a weather-resistant, easy-to-integrate, colored solar absorber [133] [42, 107] (F23). Within the *'Bionicol'* project this is further developed into a radiant facade-system with heat-insulated metallic unglazed solar absorber modules for heating, cooling and hot water storage (Figure 5) [46] (F24). The *'WICTEC CPC'* (Compound Parabolic Concentrator) curtain wall prototype contains opening wings and behind the vacuum tube collector a perforated parabolic

Figure 3: SolarWall [115]

Figure 4: TABSOLAR [44]

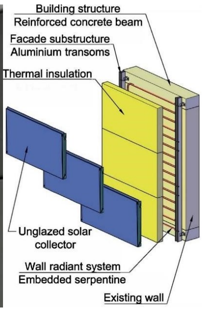

Figure 5: Facade Giovanardi [46]

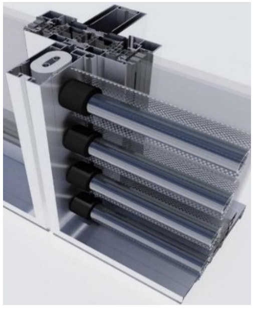

Figure 6: WICTEC CPC [125]

Figure 7: ARKOL blinds [42], strip-collector [43]

mirror for glare-free light transmission, transparency, high efficiency and shading (Figure 6) [125] (F19). The generated $60 - 90°C$ solar heat is transferred via a facade profile integrated pipe system to the building for process water, heating or solar cooling [123, 125]. The solar-thermal blinds and strip collector of the *'ArKol'* project use a spectral selective absorber to collect heat, and integrated heat pipes to extract the absorbed solar energy from the Venetian blind slats (Figure 7) [51] (F20,F21). These heat pipes are connected to vertical header tubes via a dry-thermal connection without the use of a fluid heat carrier. The condensation area has no direct connection to the solar fluid, since it is only connected to the pipe wall [48]. Since the solar fluid only flows in the collecting channel, the singular collector elements are mounted on a rear-ventilated curtain wall with typical mounting brackets and do not require a hydraulic connection. This makes the slats as mobile as blinds and reduces the thermal resistance and increases the collector efficiency [27, 42, 43]. The vertical header tubes do however require a water and a power connection.

Recently, the worlds first REG bioreactor facade was built at the BIQ Hamburg passive house (Figure 8). Bioreactor facades consist of glass louvres with 18mm cavity filled with water containing nutrients which convert daylight and CO_2 to algal biomass and O_2 through photosynthesis. At the same time the water is heated up by solar-thermal effects. In a plant room, the heat is removed from the culture medium by a heat exchanger, and the biomass is harvested by a separator [19]. The *'SolarLeaf'* (F29) slats, for example, produce $30kWh/m^2a$ biomass and $150kWh/m^2a$ solar heat based on the solar irradiation in the German city Munich [19], covering one third of the heating requirements of the BIQ building [8]. Such flat plate bioreactors (F28) can achieve an optimal photosynthetic effect equaling $50kg/m^2a$ of CO_2 due to the high surface-to-volume ratio [77]. Since Germany has 980 hours per year effective sunlight [69], locations with more sun-hours like Australia will likely show higher microalgae growing rate. However, such locations may also pose yet to explore issues due to overheating [127]. Since algae facades produce a large amount of thermal

Figure 8: BIQ Hamburg building with algae-facade [19]

Figure 9: Blade-less wind-turbine [26]

energy, they are particularly suitable for places with high domestic hot water demand such as residential buildings. The advantages of bioreactor facades lie in replacing current glazing while improving shading and daylight transmission. They improve the air quality through CO_2 absorption and O_2 production [77]. Furthermore, biomass can easily be stored as compared to expensive batteries [19]. The disadvantages of the technology include contamination, cleaning, high investment costs, conversion, complexity and competition [126, 127] as well as the required plant room and water connections to the building core.

FI converters for wind energy can either use classic wind turbines with rotating blades [98] or blade-less turbines [52], such as those using falling water drops, like *'AerovoltaicTM'* [108] generating about $10W/m^2$ or the Electrostatic Wind Energy Converter (*'Ewicon'*) with 1-2% efficiency equaling $2.3W/m^2$ (Figure 9) [26, 87, 93] (F26,F27). Due to the lack of moving parts, the latter is low-maintenance, noiseless and safe for birds. Although REG using wind turbines in the open field is the largest REG source in Germany [14], the savings CO_2-equivalent for wind-based FI REG is currently low. This is likely due to technical difficulties and low efficiencies due to wind patterns in the built environment. *'Aerovoltaic'*, however, expects a capacity increase to $100W/m^2$ in the near future, making this technology a promising future alternative for self-sufficient facades, especially since, contrary to the alternatives in this review which are all solar based systems, wind energy can be generated day and night.

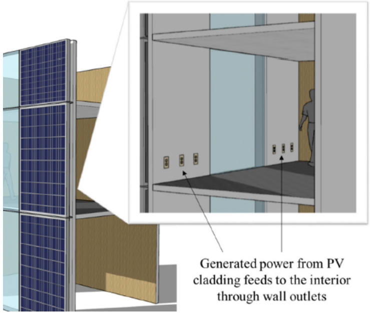

Figure 10: BPPL facade [76]

Figure 11: Coolskin [32]

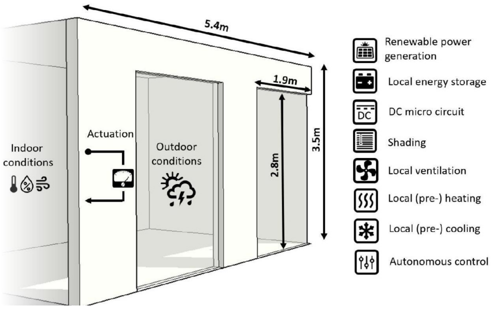

Figure 12: Facade-module CTU Prag [86]

4. Facade-integrated energy storage (RES)

Energetic self-sufficiency goes beyond energy-neutrality, and requires means of energy storage, for example using batteries. Most reviewed FI REG systems require a grid-connection due to the absence of FI RES. Few attempts to integrate batteries are researched (F1,F2,F6,F9), which, combined with BIPV, provide a high potential for self-sufficient facades. The *'smart-IoT'* facade with BIPV has a small FI battery capable of supplying enough power for the FI blinds and window control system [7] (F2). The *'Building Perma-Power Link'* (BPPL) facade panels with tilted BIPV proposes the integration of plug-points and $300W$ lithium ion batteries with dimensions of 201mm by 201mm by 79mm for office lighting (Figure 10) [76] (F1). The *'Coolskin'* project developed a cold facade system with FI battery, inverter and air-conditioning (Figure 11). Findings show that a $2kWh$ battery bridges the gap between PV-yield and electricity consumption for cooling only [32] (F6). The facade thickness however appears not suitable for thin prefab facades. The *'autonomous curtain wall panel'* (Figure 12) is an adaptive curtain wall module with FI heating and cooling via thermo-electric cells, ventilation, shading, lighting, PV and a flat-plate battery [86] (F9). Although the aforementioned research shows concepts, interest and a high potential towards FI electrical storage to achieve self-sufficient facades, research on the practical implications of FI batteries – i.e. sizing, fire risks[2], construction details, dimensions – in thin prefab facade systems is scarce. Some studies avoid these practical implications by exploring FI REG combined with external batteries (F7,F8,F26,F27) or thermo(-chemical) storage (F25,F28,F29).

Despite the volume and weight associated with water thermal storage, some studies (F11,F15,F22,F24) have explored integrating storage tanks in curtain walls. None of these seem to, however, be self-sufficient without a water supply connection. Sorption storage (to (de)humidify the supply air) (F17,F18) could,

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[2] a detailed discussion on the matter is beyond the scope of this paper.

however, be self-sufficient and appears an easily implementable and light-weight technology to combine with other HVAC technologies in light-weight prefab facades.

Although the aforementioned research expresses a genuine interest towards self-sufficient facades with FI REG and RES, no detailed design, construction or test results let alone products ready for market were found publicly available in this review [117]. Some self-sufficient buildings (B17) have, however, been built in recent years, indicating the demand for and trend towards self-sufficiency and local REG and RES (B18-B20). The apartment building from ABB is an off-grid building with no connection to the public electricity grid, oil, wood fuel or other fossil substances [2] (B17). The energy required is obtained from roof-integrated (RI) mono-crystalline PV cells and FI thin-film cells. Just one hour of solar radiation in summer is enough to supply the nine apartments with electricity for an entire day. Excess electricity is stored in lithium iron phosphate batteries, which can then generate hydrogen by electrolysis and store it in two storage tanks. This energy can then be used on cloudy days in the winter. However, the building not only requires electricity but also heat, so that part of the solar energy obtained is fed into the thermal storage system, which can then operate the heat pump [64]. The residents of each floor of the NeighborHub building generate their own electricity with FI PV [132] (B18). The KfW Efficiency House 40 Plus with six apartments generates 70% of its electricity and heat requirements from solar energy in the form of $96m^2$ RI solar thermal collectors and $196m^2$ PV on the roof, facade and balconies. Surpluses from the house systems and from the regional energy supplier are stored in a $20{,}000l$ long-term water thermal storage and two solar power batteries [11, 64] (B19). The Alstonvale Net Zero House (concept) with RI solar thermal and BIPV and reuse of captured PV-rear heat, a $4000l$ water tank and a heat storage tank and two small heat pumps, can be 70% energy-neutral in February, the coldest and least sunny month in Canada [15] (B20). These examples show, that under the right circumstances it is possible to fully cover the building demand solely with FI REG (B18), that off-grid can be achieved with a combination of electrical and thermal storage (B17), and examples towards self-sufficiency found are low to medium-rise residential lighthouse projects (B17,B18,B19,B20).

5. Facade-integrated HVAC

5.1. Facade-integrated decentralised ventilation

FI decentralized ventilation (DV) can provide various benefits as compared to centralized ventilation (CV). The lower efficiency of the smaller decentralised fans is compensated by the shorter air channels and, therefore, reduced pressure loss of DV [85]. Except for open offices, DV often goes paired with energy-savings for the fresh air supply ($< 1\ W/m^3s$) and conditioning, as devices run only in occupied rooms with

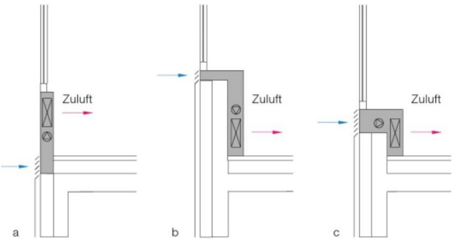

Figure 13: Facade-integrated decentralized ventilation [55]

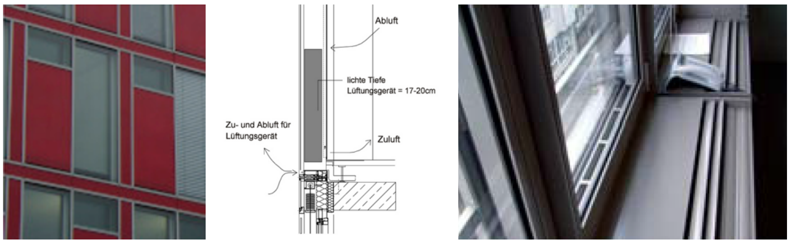

Figure 14: Parapet ventilation at Capricorn Haus [104] [40] (left) and at Siedlungsworks (right) © BINE Informationsdienst FIZ Karlsruhe

variable supply air flow (VAV) [12, 37, 41, 55, 75, 85, 128] (B1,B3,B4,B6,B7,B8). This variable supply leads to higher user acceptance through individual control / adjustable setpoints, and allows for room or zone-specific energy consumption payment. As defects only affect one room, retrofitting is easier and there is a greater flexibility to variable room occupancy. DV further leads to space-saving for shafts, control rooms, fire dampers and false ceilings due to the absence of air channels [41, 55, 78]. Furthermore, considering the recent pandemic COVID-19, DV benefits related to reduced chance of spreading infections by eliminating air re-circulation and heat recovery between rooms have gained interest [89].

The investment cost for DV can, however, be equal or slightly higher than that of CV [55, 78, 85]. There could also be problems with noise and draft in case of too high ventilation flows [85]. With DV the wind pressure and outdoor temperature at the facade may affect the functionality of the equipment, e.g. frost-protection. Maintenance, filter change, heat recovery and (de)humidification can further be difficult or costly in occupied rooms. If there is no de-humidification, the cooling capacity of the equipment is limited due to condensate limits [55, 78].

To pre-condition the fresh supply air, the DV can be combined with a decentralised heating, cooling and (de)humdification system (FI HVAC) and/or a decentralised heat and humidity recovery system. There are DV systems (with or without heating register) on the market that only require a power supply; no further ducting or pipe-works are required, making them self-sufficient in combination with a suitable renewable energy source. Those including heat and humidity recovery [25], however, are suitable for facades with thickness over 300mm, as they are conceptualised for thick brick or timber-structure walls that are common for low-rise buildings. Hence, none of the market-available FI DV systems with in-built heat and humidity recovery found, fits thin facade systems that are common for high-rise buildings.

FI decentralised HVAC has become increasingly popular in medium to high-rise buildings [37, 56, 57, 60, 80, 85, 88, 96, 99, 121, 128] (B1-B16). Between the year 2000 and 2006 about 50 buildings have been

Figure 15: HVAC in TEmotion-Module [122]

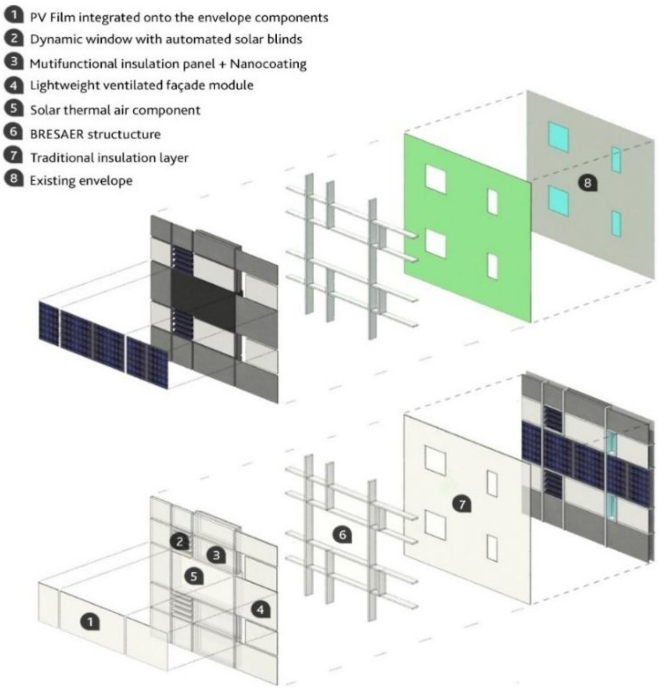

Figure 16: BRESAER system built-up [3]

realized with FI HVAC in Western Europe [84]. FI HVAC systems are often integrated in the parapet using a VAV HVAC unit like the *'TROX i-Modul'*, which provides demand-based fresh air and free summer night cooling (Figure 13, Figure 14) [84]. Those HVAC units, however, although efficient, are liquid-based and require pipe-works from the facade to the building, and are therefore not completely self-sufficient. Further, they do not fit thin facades, let alone after adding the facade insulation [116].

Few facade-systems on the market combine multiple strategies in a prefab facade-system. The *'TEmotion'* system from WICONA, with integrated PV, HVAC, blinds, and automated, sensor-based operation aims to achieve a high level of self-sufficiency and room-conditioning (Figure 15) [6, 122]. Grid and water connection are however required [116, 124] (F3). The *'BRESAER'* system combines 5 components already on the market; a solar thermal air heating panel (*'SolarWall®'*), a lightweight insulation facade module with lightweight concrete from ULMA, dynamic windows from ASCAMM, a ventilated facade module, the multifunctional UHPFRC panels from Stam, and PV-modules (Figure 16) [3] (F13). Depending on the floor area and climate, between 40% and 70% energy savings can be achieved [16]. A grid connection is, however, required.

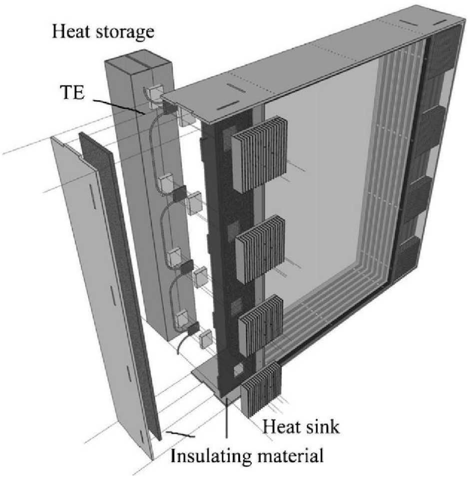

Figure 17: Visualisation of Xu's concept [129]

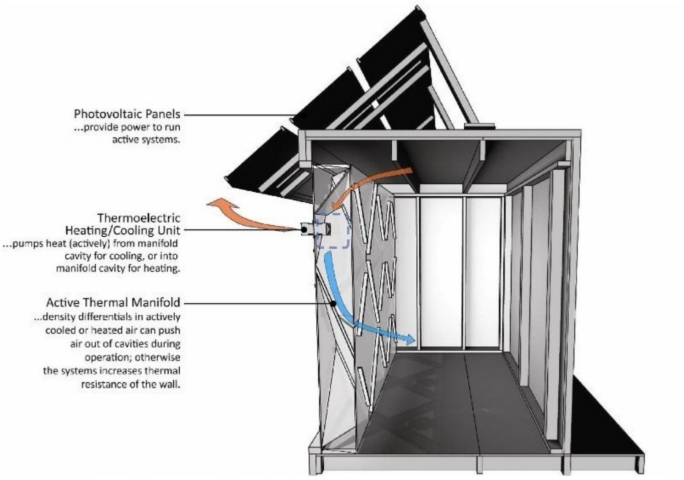

Figure 18: Visualization of Gibson's prototype [45]

5.2. Facade-integrated heating and cooling

Complete self-sufficiency occurs with energetic self-sufficiency combined with the absence of cables, supply and drainage lines to the building. Thermo-electric (TE) elements are most promising in this respect, considering the little space requirement, absence of a complex distribution system or pipe-works to the building core, and the flexibility to provide both heating and cooling on demand [104]. The condensate that may occur in some of these systems could namely be drained via the facade or via a removable drain tray. Further advantages of FI decentralized TE room-conditioning systems are primarily *'missing moving parts, lack of noise, low maintenance, the identification of local requirements and electronic control'*, which make the system both economical and energy-efficient, although TE modules itself are less efficient than vapour compression systems [45, 102, 105]. The drawback is, that the efficiency depends on the cooling capacity [102]. FI TE solar cooling technologies, although commercially not available, have come into focus in recent years due to the increasing cooling demand [95, 101, 102, 104]. Cooling energy demand of the residential and commercial buildings represents 2.9% and 6.7% of the total world energy consumption, respectively, and is expected to increase up to 750% and 275% by 2050 [109].

Most technologies are based on electrical or thermal processes [105]. The TE systems operate directly through PV without the need for an AC / DC converter, and uses environmentally friendly working materials in the cooling process (no harmful refrigerant) [102]. The technology can be used, for example, in solar TE air-conditioning systems [83]. Natural convection via a heat sink can absorb or dissipate heat from the outside environment. Simulations of a facade module with PV, TE modules and vertical aluminum pipes

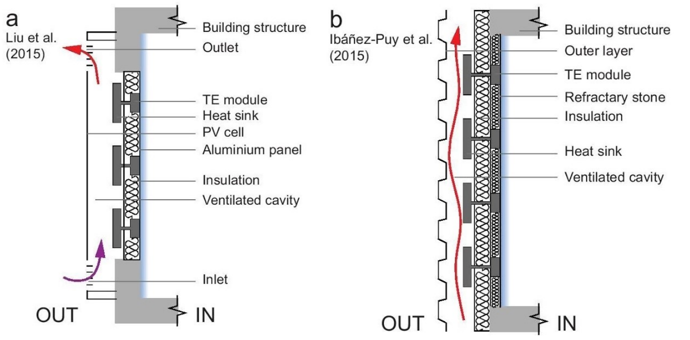

Figure 19: Facade-concept by Liu (left) and Ibáñez-Puy (right) [105]

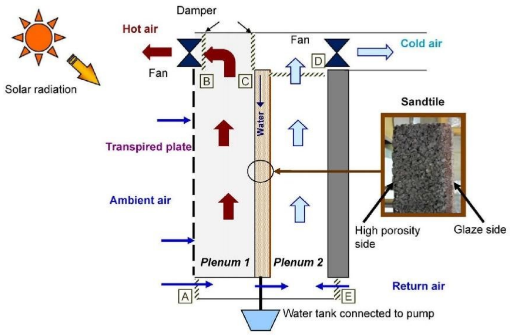

Figure 20: Facade-concept by Chan [17]

with water as heat transfer medium show, that the module has an influence of 2 to 6°C on the room temperature and can also provide 35 to 45W energy per module (Figure 17) [129] (F11). Also based on TE Peltier cells, but filled with air as a cooler, is the prototype from Gibson coupled with 85W PV panels and a 72W TE cooling unit (Figure 18) (F10). It was found that not the cooling side, but the heating side of the TE module affects the performance [45]. Alternatively, the PV-modules, which supply current to the TE modules, can emit heat into the inner layer of the wall via an aluminum radiant panel (Figure 19, left) [83, 104] (F12). With 20 Peltier cells in a facade module with dimensions 1.2m * 1.8m * 0.25m a total output of 1000W can be achieved (Figure 19, right) [65] (F14). Experiments on a solar cooling facade with a multi-layer structure (Figure 20) show that with the addition of 0.52 W auxiliary energy, 1 kW energy can be generated to cool the air [17] (F15).

Besides power-sourced FI HVAC technologies, technologies using solar thermal energy are widely researched. Systems using solar thermal energy can be divided in those using a gas like air as a medium and those using a liquid as a medium. Although systems using liquids as a medium have a higher efficiency, they require pipe-work to the building and are, therefore, less suitable for standalone self-sufficient facades. Instead of PV, the outer layer of a solar cooling facade can, for example, be in the form of a rear-ventilated solar collector to regenerate a desiccant behind [39, 104] (F17). The lower part of the *'iNSPiRe'* curtain wall unit (Figure 21, Figure 22) contains the patented glass-covered triple-state absorption module. Simulations in TRNSYS show a reduction in cooling requirements of 15 to 40% (east/west orientation) [9, 10] (F18). To increase user satisfaction the unit was further developed with a ventilation system with heating and cooling coil (aeraulic box) connected in series with the sorption collector [13] and by integrating a solar water tank (dimensions 1.2m * 1.3m * 0.06m, 46 L) between the thermal collector and the radiator panel [23] (F22).

Numerical simulation results of a 16m^2 office room with 6.8m^2 FI PV or ST comparing TE, desiccant

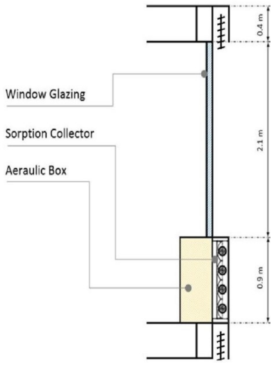

Figure 21: Facade-system iNSPiRe 2016 [13]

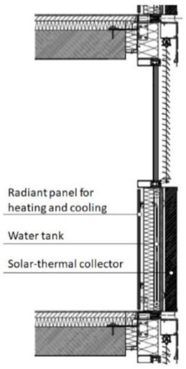

Figure 22: Facade-system iNSPiRe 2018 [23]

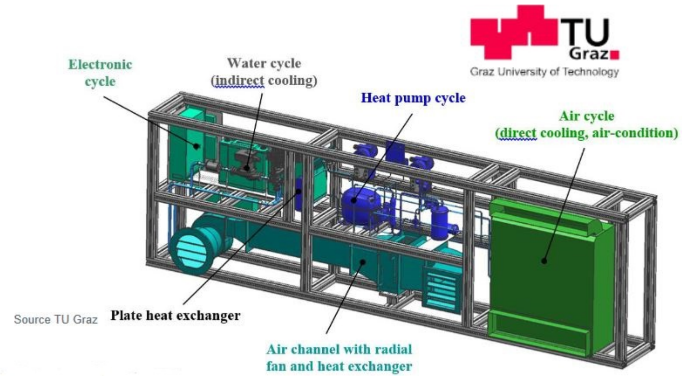

Figure 23: Facade-integrated heat pump [32]

and sorption solar cooling indicate, that although warm-dry temperate climates and east/west orientations are most suitable, solar cooling facades are feasible in almost every climate region and orientation provided the cooling loads are reduced with passive measures [102, 105]. It has to be noted, that the simulations were conducted without considering other types of energy to power up additional equipment, such as pumps for absorption heat pumps, or evaporative cooling units for desiccant systems. On the other hand, thermoelectric cooling is driven by direct current, so an inverter and the subsequent derived losses do not need to be considered in the calculations. Based on [102], the capacity to be met by the FI solar cooling systems ranges 0.8-1.8kW depending on the orientation and climate. Comparing the above solar cooling technologies, solar electric systems are more constrained due to lower efficiencies of PV as compared to solar thermal collectors, and limited TE efficiency. Hence, self-sufficient facade modules for commercial buildings are only theoretically feasible on east orientations in temperate dry climates like Lisbon. TE solar cooling facades are more suitable for temperate dry climates with small cooling loads, whereas desiccant solar cooling facades are particularly suitable for humid climates, since the desiccant removes latent loads. As sorption techniques require a higher temperature to operate, they are more suitable for hot dry climates [102].

An alternative use of BIPV for self-sufficient FI HVAC is the integration of heat pumps (HP), mechanical ventilation (MV) and batteries, such as in the *'COOLskin'* facade project (Figure 23) [32] (F6). Simulations of the *'HVACviaFacade'* system installed in front of an existing facade and consisting of PV, blown insulation (per thermal insulation standards for a low-energy house and for a passive house) and a HP showed energy savings up to 70% [67, 71] (F7). About 24% of the FI HP with secondary air recirculation energy consumption is covered by the FI PV in the *'SaLüH!'* project, short for *'Sanierungsansätze für Lüftung, Heizung und Warmwasser'* (renovation approaches for ventilation, heating and hot water) [94] (F8).

6. Summary and conclusion

All facade systems and building application studies analysed (except B9's historical in-situ facade) integrate REG, RES or HVAC in a prefab facade system; mostly in an unspecified curtain wall (B8,B13,B14,B15, B16,F1,F4,F5,F7,F9,F15,F18,F20,F22,F28), double-skin curtain wall (B2,B6,B7,B11,B12,F2,F10,F26,F27, F29) or unitized curtain wall (B1,F3,F6,F19), some in a rear-ventilated (F12,F14,F17,F21) or perforated facade (B3,B5,B9,B10), or in a ribbon window (B4), prefab timber (F8) or retrofit (F13) facade. Studies of FI wind-energy, photobioreactors and electrical storage reviewed are solely for curtain wall integration. Except for one study, all building applications of FI HVAC reviewed are in office buildings, whereas all building applications with REG and RES reviewed are residential.

High-rise building facades offer a high REG potential [38], and thin prefab curtain walls such as unitized systems provide the additional benefit of space saving and quick on-site large-scale application. Most facade-systems with FI REG use solar energy; 13 FI PV and 13 FI ST are compared in this paper, compared to 2 wind-energy and 2 photobioreactor facade systems. It can be concluded from the CO_2-comparison in Table 1, that FI ST heating and thermochemical systems in most studies provide highest CO_2-equivalent savings (22-63kg/m^2a). This is followed by FI systems combining PV with HPs (14-32kg/m^2a), PV supporting electrical loads such as blinds (9-34kg/m^2a), and FI wind-energy (4-19kg/m^2a). FI cooling systems, such as those combining PV with TE modules or ST with sorption or desiccant systems, provide significantly lower savings (1-11kg/m^2a) due to their low COP. The order of magnitude of these findings are in line with their respective efficiencies. Comparing FI REG technologies, ST systems have efficiencies in the range 60-65%, where the efficiency of the conversion of light to biomass is 10% and to heat 38% for bioreactor facades [19]. Since bioreactors in the process of conversion to biomass also absorb CO_2, the resulting CO_2-savings are high. For comparison, PV systems have an efficiency of around 20% [118] and FI wind turbines have tested efficiencies around 1-10% [22, 108]

Systems using liquids as medium – i.e. REG (F19-F25,F28,F29), RES (F11,F21,F23,F28,F29) and HVAC systems (B1-B16,F3,F6,F7,F11,F19-F25,F28,F29) – are, however, not suitable for self-sufficient prefab facades due to the required supply and drain lines to the building core and the related difficulties between different trades in the planning phase and at the construction site. These include bioreactors, which require spacious plant technology, water-based ST REG or RES and conventional vapour compression systems. Solar energy, unless water-based, provides opportunities for self-sufficient facades (F1,F2,F4,F5,F9-F10,F12-

F14,F16-F18) if combined with FI RES. The review, however, found no water-less RES for FI air-based ST. Hence, from the perspective of self-sufficiency, wind-energy (F26,F27) and BIPV (F1,F2,F4,F5,F9,F10,F12) provide the best opportunities, as they can be combined with electrical storage. One study (F27) claims 10-fold REG improvement predictions for FI wind-energy, which could result in significantly higher savings $\mathrm{CO_2}/m^2$-equivalent than BIPV.

It can further be concluded, that a trend towards decentralised FI HVAC has developed over the past two decades (B1-B16). Furthermore, most buildings with FI HVAC appear to provide CO_2-savings as compared to reference buildings with centralised HVAC (B1,B3,B4,B6,B7,B8). The current trend, however, exclusively appears to use water-based heating and cooling systems that are not self-sufficient. Among the FI HVAC analysed, few (F4,F5,F8,F9,F10,F12-F15,F16,F17,F18) function without liquid/water connection to the building core, using air as a medium. Amongst those, however, only systems using air-to-air HP or TE elements (F8,F9,F10,F12,F14) could provide full HVAC functionality including heating, cooling and ventilation. Thus, the implementation of FI solid- or air-based heating and cooling systems, such as DV units (with in-built heat and humidity recovery) combined with TE elements, (sorption) HPs or desiccant systems, provides great opportunities from a FI self-sufficiency perspective, although commercially not available.

Equally unexplored are FI (high capacity) batteries for local RES (F1,F2,F6,F9), despite their potential for self-sufficiency, in particular in combination with BIPV and wind-energy. Hence, further research in the area of FI batteries is required in terms of capacity, sizing and fire safety.

The analysed FI HVAC with full HVAC functionality are either self-sufficient in terms of energy (F1,F2,F6, F9) or in terms of absence of water and waste supply / drain lines to the building core (F8,F9,F10,F12, F14). Hence, the current market lacks prefab self-sufficient facade systems with FI HVAC capable of supplying their energy demand with self-generated and stored energy, eliminating the need for a grid or water connection to the building core. Amongst all reviewed studies F9 is the only one that meets all criteria. However, the concept seems to not have materialized in a fully tested prototype yet, as it lacks publicly available details on construction, storage and sizing. Research and development of prefab thin facade systems with BIPV or wind-energy, FI electrical storage, DV with heat and humidity recovery and TE modules or air-to-air HPs could bridge the gap towards self-sufficient facade systems, as is necessary for the long-term achievement of the climate policy goals.

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