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MULTI-CRITERION ANALYSIS OF SELECTED POWER MANAGEMENT STRATEGIES IN SMART HOME SYSTEMS

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Abstract: The introduction of renewable energy sources (RES) and modern building automation solutions, known as smart homes, has greatly increased building energy efficiency. The number of smart home solutions and their elements in closed and open systems continues to grow. This paper attempts to present the energy management abilities in KNX smart home systems based on two different strategies applied to two model houses. Solutions based on a cost-effective strategy and solutions based on a comfort strategy were selected for a multi-criterion analysis based on an electric energy balance in selected buildings, economic analysis and analysis of the selected solutions in terms of user comfort. Finally, a comparative analysis was performed for the results of the multi-criterion analysis of smart home systems combined with RES for two selected buildings.

Keywords: smart home, KNX, renewable energy sources, energy management.

1. INTRODUCTION

According to the Directive of the European Parliament and of the Council 2010/31/EU of 18 May 2010 (OJ EU L 153 of 18 June 2010, pp. 13–35), beginning on 31 December 2020, all new buildings must be characterised by almost zero net energy consumption (nZEB standard – "nearly zero-energy buildings") and zero CO_2 emissions, which means these buildings must generate as much energy from RES as they consume. The directive also introduces the concept of building energy performance, which expresses the amount of energy necessary to satisfy the energy demand from typical use of the building, including energy for heating, cooling, ventilation, hot water and lighting. Member states, including Poland, are obligated to adopt on the national or regional level a methodology for calculating building energy performance, which must include certain elements, in particular:

- building heat properties (heat performance, insulation, etc.);

- heating equipment and hot water supply;
- air conditioning installations;
- integrated lighting installation;
- internal environmental conditions.

The positive impact from other elements, such as local insulation conditions, natural lighting, electric energy production by cogeneration and metropolitan or collective heating and cooling systems are also taken into account. These regulations enforce the implementation of modern energy-saving engineering solutions.

The introduction of renewable energy sources (RES) and modern building automation solutions, known as smart homes, has greatly improved building energy efficiency. A smart home is a building that includes advanced automatic systems to provide its residents with the ability to control and monitor the functions of the building. A smart home system allows the residents to control lighting, temperature, multimedia, security, window and door operation, and many other things. Smart homes are equipped with a system of sensors and executive elements that can communicate with each other via various media, and a single, integrated systems for managing all installations located in the building. With the development of technology, especially the Internet of Things (IoT), almost every electronic element in a house can now be integrated with a smart home system via wireless communication, i.e. by network, machine-machine communication or cloud processing [Byun, Hong and Park 2012; Shoji et al. 2015; Arvind, Raj and Krishna Prakash 2016; Krishna Prakash and Surjith 2017; Yogavani and Krishna Prakash 2017]. Energy efficiency is the highest priority in designing smart home systems. The aim of the scientists and designers behind these systems is to reduce the amount of energy consumed as much as possible without degrading the convenience of use. Optimisation of energy use in buildings should be based on the following actions:

- use of energy only when necessary;
- amount of energy used from non-renewable sources should be kept to a reasonable minimum;
- maximum possible efficiency of energy use.

A home energy management system (HEMS) is an essential system for effectively managing "smart" home appliances [Brooks et al. 2010]. It monitors and plans optimum operation of various electric home devices in real time, based on user preferences set using a human-machine interface (HMI) in smart homes to reduce the costs of electric energy and improve energy use efficiency [Vojdani 2008; Farhangi 2009; Zhang, Li and Bhatt 2010]. HEMS usually formulate optimal energy consumption and production schedules, taking into account multiple criteria, such as energy costs, environmental protection, load profiles and consumer convenience [Wang and Xu 2004].

With a smart home energy management system, the user can apply different management strategies. The main energy management strategies in smart home systems are:

- Cost-effective – Energy cost reduction by using less expensive rates or using energy generated by RES for its own needs;
- Environmentally friendly, low-emissions – Reduction in greenhouse gas emissions. Minimised building emissions factor – CO_2/kWh by effective use of RES and minimisation of demand for energy from fossil fuels;
- User comfort – The system is tasked with optimally managing energy to improve the convenience of users at home;
- Load control – This strategy involves minimising grid energy demand during daily energy demand peak hours or becoming completely independent from grid energy supply.

The purpose of this paper is to present the options of shaping energy management strategies in smart home energy systems by means of a multi-criterion analysis of two sample single-family house solutions equipped with smart home energy management systems combined with RES, selected depending on the system user needs. Each of the home solutions analysed was developed based on different energy management strategies.

2. OBJECT OF THE STUDY

For the purpose of energy management system analysis, two smart home energy management system solutions were prepared based on two different energy management strategies: cost-effective and comfort. The systems in question were implemented in single-family houses.

2.1. System based on the cost-efficient strategy

The house solution with a smart home management system was based on the solution described in [Wójcicki 2016].

The performance of the house selected for analysis of the energy management system according to the cost-effective strategy is shown in Table 1.

The house is equipped with an uncomplicated energy management system comprising the following elements:

- electric energy counter monitoring energy consumption;
- Home Area Network (HAM) controller for selected home appliances.

Table 1. Performance of the energy management system-equipped house according to a cost-effective strategy

Building characteristic	Description
Plot size	1000 m^2
Location	Pomorskie voivodeship, Kosakowo municipality
Utility area	83 m^2
Number of storeys	1
Energy standard	Low energy, EP=38.6 kWh/(m^2*year)
Structure	• aerated concrete blocks, 24 cm thick, • external wall heat insulation with expanded polystyrene, 19 cm thick, • double-sloped roof, tile-covered, • roof heat insulation with mineral wool, 30 cm thick
Renewable energy sources	• 10.13 kWp on-grid photovoltaic installation, • 10 kW ground heat pump

Source: prepared by authors.

The selection of home appliances subject to the management system was based on the intent to maintain user convenience at an unchanged level, home appliance energy consumption and ease of control. The devices selected are refrigerator, laundry machine and dishwasher. The concept diagram of the prosumer installation with a smart home energy management system is shown in Figure 1.

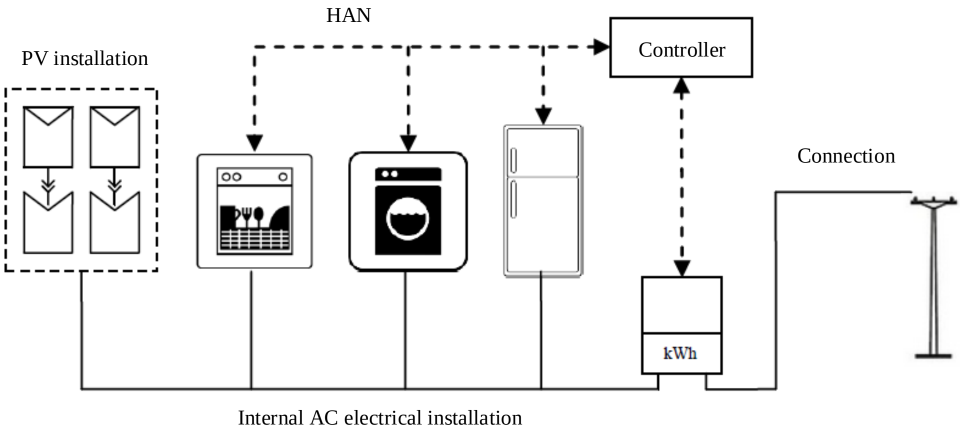

Fig. 1. Concept diagram of the prosumer installation in the cost-effective building

Source: [Wójcicki 2016].

The premise of this strategy was to minimise energy costs for the operation of selected devices, while at the same time maximising the use of energy generated by the photovoltaic (PV) microinstallation, and to reduce the demand for electric energy in the building during daily grid power demand peak hours. The equipment control scenario involves activating the washing machine and dishwasher independently after the PV installation reaches a pre-set power level – ratio of current RES power to top rated power of the controlled equipment, which was 2 kW. In this case, 61% of the home appliance energy demand can be expected to be covered by the RES.

To ensure correct functioning of the home appliances, certain assumptions were taken into account in the algorithm:

- refrigerator operation may not be restricted due to the necessity of maintaining the set operating temperature range of the refrigeration compartment;
- once the washing machine or dishwasher is activated, their operation may not be interrupted in order to accomplish their intended purpose;
- the washing machine must be activated every 3 days and its work cycle must be completed before 17:00 hours;
- the dishwasher must be activated every day and its work cycle must be completed before 16:00 hours;
- unconditional activation of the dishwasher at 12:00 hours and the washing machine at 13:00 hours to ensure these devices are activated regardless of insulation.

In the analysed building, the total annual electric energy consumption in 2015 (that year the most data were received) was 7485 kWh – this is the value achieved without a smart home system installed. 2763 kWh of electric energy were used for the purpose of heating the building with a heat pump. A PV microinstallation with a 10.13 kWp power level generated 9639 kWh of electric energy during the year. At the beginning of 2016, an energy management system for the PV installation was added to the house for the purpose of powering the 3 home appliances. The estimated electric energy consumption for the home appliances in question was approx. 506.99 kWh per year. The investment for installing the house solution based on the cost-effective strategy was approx. PLN 56,191.36.

2.2. System based on the comfort strategy

The performance of the house selected for analysis of the energy management system according to the comfort strategy is shown in Table 2.

Table 2. Performance of the energy management system-equipped house according to comfort strategy

Building characteristic	Description
Plot size	1000 m^2
Location	Pomorskie voivodeship, city of Gdynia
Useful area	118 m2 (ground floor: 61.6 m^2, attic: 56.4 m^2)
Number of storeys	2
Energy standard	Low energy, EP = 57.6 kWh/(m^2*year)
Structure	• two-layer sand-lime blocks, 18 cm thick, • external wall heat insulation with expanded polystyrene, 18 cm thick, • double-sloped roof, snap-lock sheet-covered, • roof heat insulation with mineral wool, 30 cm thick
Renewable energy sources	• 14.35 kWp on-grid photovoltaic installation, • 12 kW air heat pump HT10/12 type, • mechanical ventilation with an earth-air heat exchanger (EAHE) – WANAS 550 V/3, total power approx. 1 kW

Source: prepared by the authors.

To achieve high user comfort, the user was equipped with a smart home installation. The system comprised the following elements:

- visualisation of the entire smart home system on the building map using a visualisation server combined with a 10” LCD touch panel and data cloud;
- heating control using thermostatic heads on Danfoss heaters and a Modbus TCP/RTU gate on KNX;
- ventilation control using a single-channel activation operator;
- lighting control performed by 4-channel dimming operators, presence sensors, wall-mounted switched and, in some rooms, light sources with integrated wireless control;
- selected electric devices or entire electric circuits controlled via activation modules in the building’s main switchboard or using wireless-controlled electric socket inserts;
- operation of selected home appliances, video and audio equipment managed using IoT technologies;
- electronic door lock system, colloquially referred to as smartlocks;
- video intercom system manageable anywhere via a mobile application or from a stationary LCD panel at home;
- home-based electric energy consumption monitoring system utilising electric energy counters, activation modules in the main building switchboard or electric socket inserts with current monitoring;
- electric energy production monitoring system in the PV installation using data provided by the inverter.

The user can manage the system using a stationary LCD touch screen installed in the building, as well as remotely from any location using a cloud-based application.

In the analysed building, the estimated total annual electric energy consumption was 10,789.74 kWh. A PV microinstallation with 14.63 kWp power generated 13923.00 kWh of electrical energy during the year. The investment expenditure for installing the house solution based on the comfort strategy was approx. PLN 137,267.00.

3. EVALUATION CRITERIA FOR THE STUDIED ENERGY MANAGEMENT SYSTEMS

The following comparison criteria were applied in the multi-criterion comparative analysis for solutions based on selected energy management strategies utilising smart home installations:

A. Electric energy consumption analysis – Electric energy balance of the adopted house solutions, prepared using a direct method by analysing energy consumption or production of individual system elements.

B. Economic analysis (Profitability) – To perform an economic analysis of the developed house solutions based on the selected energy management strategies, economic calculations using two economic performance assessment methods were performed:
   - static method: simple pay back time (SPBT);
   - dynamic method: net present value (NPV).

The SPBT static method was the simplest, intuitive method of evaluating the economic performance of the investment. It determined how much time is needed for the investment expenditure made to complete the undertaking to pay for itself. The SPBT index can be expressed with the following equation:

$$\text{SPBT} = \frac{I}{Z_i} \tag{1}$$

where:

I – investment expenditure amount [PLN],
Z_i – total profits in year i (i = 1,2,..., n) [PLN].

This index was characterised by its orientation value and great simplicity. A drawback of this method was that it failed to account for currency value changes over time.

0.7 kWh for each 1 kWh given to the power grid (option for installations with power above 10 kWp) during a settlement period of 12 months. If energy from a photovoltaic installation were used for the purposes of a house, it could be expected that about 20% of the annual power demand of the other home appliances would also be covered from the photovoltaic installation (estimate based on [Horyński 2015]). This resulted in a consumption of about 1865.95 kWh for household needs, with the remaining 7463.79 kWh transferred to the power grid. 5224.65 kWh could be withdrawn from the grid via virtual energy storage, which would be more than enough to cover the increased electric energy demand of the heat pump during the heating season, which amounted to 2763 kWh. It was calculated that about 7399.86 kWh of the energy savings were achieved through the use of a photovoltaic installation and energy management system. The estimated electric energy drawn from the distribution grid should therefore be about 85.14 kWh annually.

For the solution based on the comfort strategy, the consumption would be estimated at 10,789.74 kWh/year. This included 3504 kWh of the electrical energy used per year for the purpose of heating the building and providing hot utility water with a heat pump. A photovoltaic installation with 14.63 kWp power generated 13,923 kWh of electric energy during the year. As in the previous case, based on the cost-effective strategy, it could be assumed that the electric energy demand of the smart home energy management system would be partly covered – the predicted factor was 30%, which translated to 4176.9 kWh of electric energy produced in the photovoltaic installation for the household's own needs. The remaining energy produced by the photovoltaic panels could be transferred to the grid and withdrawn at a later time, at a ratio of 1 to 0.7 (value for PV installations with ≥10 kWp power), 6822.27 kWh can be obtained this way. The total would be 10,999.17 kWh per year, a value greater than the estimated annual electric energy demand of 10,789.74 kWh. The remaining 209.5 kWh of energy could be used, for example, to heat the pavement in front of the house entrance during the winter season, when temperatures drop below 0°C, or to charge an electric car.

4.2. Economic analysis – profitability

Tables 3 and 4 show estimated cash flows based on the returns assessment of the studied installations using the above method and based on estimated data:

- total (including all elements) price for electric energy [electric energy prices in Poland 2021] – 0.67 PLN/kWh;
- production efficiency drop in the PV installation: 0.7% per year;
- predicted energy price rise: 5% per year;
- investment cost of individual smart home installations;
- averaged annual electric energy production of individual studied smart home installations;

- settlement-based profit calculation system: PV installation: 70% – on-grid prosumer system;
- estimated electric energy savings;
- number of yearly calculation periods n = 20;
- assumed rate of return based on long-term state treasury bonds r = 2.5%.

Note: Installation operational costs were not taken into account.

Table 3. Cash flow estimated from depreciation assessment of the solution in question for a home based on the cost-effective solution

Year [years]	Current and estimated Price per 1 kWh	Estimated energy benefit	Financial benefit	Cash flow	Discounted cash flow NPV
	[PLN]	[kWh]	[PLN]	[PLN]	[PLN]
0		Investment cost >		-56,191.36	-56,191.36
1	0.67	7,399.86	4,957.91	-51,233.45	-51,354.38
2	0.70	8,083.79	5,686.95	-45,546.50	-45,941.46
3	0.74	8,027.51	5,929.72	-39,616.78	-40,435.12
4	0.78	7,971.62	6,182.86	-33,433.92	-34,833.76
5	0.81	7,916.13	6,446.81	-26,987.11	-29,135.71
6	0.86	7,861.02	6,722.03	-20,265.08	-23,339.33
7	0.90	7,806.30	7,009.00	-13,256.09	-17,442.91
8	0.94	7,751.96	7,308.22	-5,947.87	-11,444.71
9	0.99	7,698.00	7,620.22	1,672.35	-5,342.99
10	1.04	7,644.42	7,945.54	9,617.89	864.06
11	1.09	7,591.22	8,284.75	17,902.64	7,178.23
12	1.15	7,538.39	8,638.44	26,541.08	13,601.40
13	1.20	7,485.92	9,007.24	35,548.32	20,135.44
14	1.26	7,433.83	9,391.79	44,940.11	26,782.26
15	1.33	7,382.10	9,792.75	54,732.86	33,543.82
16	1.39	7,330.73	10,210.84	64,943.70	40,422.10
17	1.46	7,279.72	10,646.78	75,590.48	47,419.11
18	1.54	7,229.07	11,101.33	86,691.82	54,536.90
19	1.61	7,178.77	11,575.30	98,267.12	61,777.58
20	1.69	7,128.83	12,069.50	110,336.62	69,143.24

Source: prepared by the authors.

The SPBT index is calculated below:

$$\mathrm{SPBT} = \frac{56\,191.36}{4\,957.91} = 11.33 \text{ years} \tag{3}$$

Table 4. Cash flow estimated from depreciation assessment of the solution in question for a home based on the convenience solution

Year [years]	Current and estimated Price per 1 kWh	Estimated energy benefit	Financial benefit	Cash flow	Discounted cash flow NPV
	[PLN]	**[kWh]**	**[PLN]**	**[PLN]**	**[PLN]**
0		Investment cost >		-137,267.00	-137,267.00
1	0.67	10,789.74	7,229.13	-130,037.87	-130,214.19
2	0.70	10,789.74	7,590.58	-122,447.29	-122,989.37
3	0.74	10,789.74	7,970.11	-114,477.18	-115,588.33
4	0.78	10,769.80	8,353.15	-106,124.03	-108,020.79
5	0.81	10,694.41	8,709.41	-97,414.62	-100,322.93
6	0.86	10,619.55	9,080.87	-88,333.75	-92,492.53
7	0.90	10,545.21	9,468.17	-78,865.58	-84,527.29
8	0.94	10,471.40	9,871.99	-68,993.59	-76,424.89
9	0.99	10,398.10	10,293.03	-58,700.56	-68,182.97
10	1.04	10,325.31	10,732.02	-47,968.54	-59,799.13
11	1.09	10,253.03	11,189.75	-36,778.79	-51,270.92
12	1.15	10,181.26	11,666.99	-25,111.81	-42,595.87
13	1.20	10,109.99	12,164.58	-12,947.22	-33,771.43
14	1.26	10,039.22	12,683.40	-263.82	-24,795.04
15	1.33	9,968.95	13,224.35	12,960.53	-15,664.08
16	1.39	9,899.17	13,788.37	26,748.90	-6,375.89
17	1.46	9,829.87	14,376.44	41,125.35	3,072.24
18	1.54	9,761.06	14,989.60	56,114.95	12,683.06
19	1.61	9,692.74	15,628.91	71,743.85	22,459.37
20	1.69	9,624.89	16,295.48	88,039.33	32,404.03

Source: prepared by the authors.

The SPBT index is calculated below:

$$\text{SPBT} = \frac{38\,998.86}{5\,215.41} = 11.16 \text{ years} \tag{4}$$

Figure 2 shows the discounted cash flows in individual years for both house solutions. Square symbols mark the comfort strategy flow, while round symbols denote the cost-effective strategy flow. The flow crossing the PLN 0 point means that the solution based on the selected strategy paid for the investment expenditure paid to install it. When either flow reaches positive values, it means the investment has begun to bring profits.

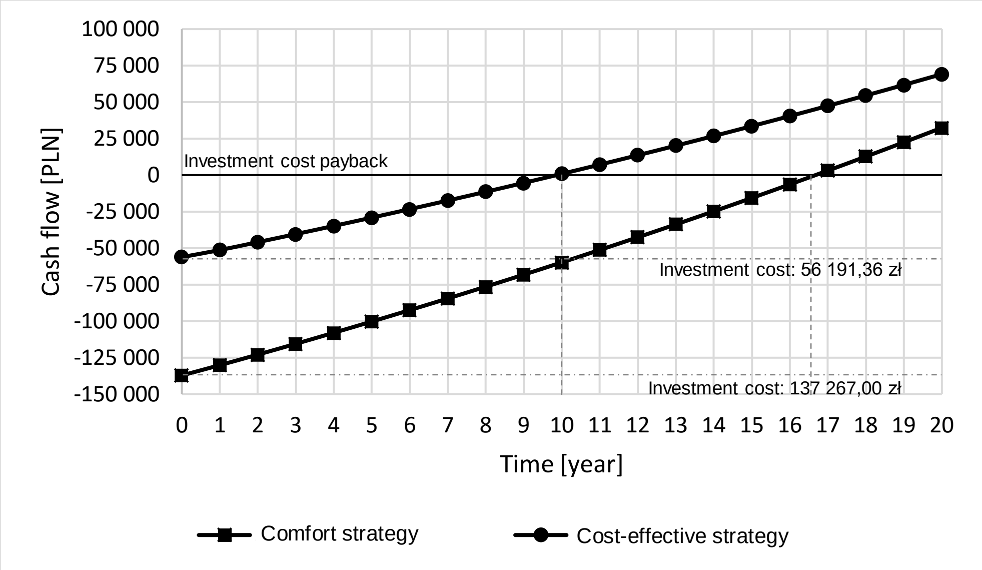

Fig. 2. Cash flow over time for the houses analysed

Source: prepared by the authors.

The smart home installation for the house solution where the cost-effective strategy was assumed will pay for itself in about 10 years. Photovoltaic panels have a life of 25–40 years, depending on the generation. Considering the simplicity of this solution and the focus on a selected group of home appliances, the investment depreciation result can be considered a good one.

The payback period of the house solution where the high comfort strategy was assumed is almost 17 years, which means that in economic terms, the installation is moderately profitable or unprofitable due to the life of many devices used in the installation being substantially exceeded. It is certain that within almost 17 years, the installation will require major maintenance and modernisation work, which will further increase investment costs and extend the payback time.

It can be seen in Figure 2 that in terms of generating savings on electricity bills, both solutions have a similar potential. The flows are inclined at similar angles, which results from selecting the photovoltaic installations for both solutions so that electrical energy production in the RES covered the building's entire electric energy demand (zero-energy building).

4.3. Solution analysis in terms of usage convenience

Table 5 compares the smart home energy management system solutions in terms of elements or characteristics that improve a given system convenience of use, according to the energy management strategy adopted.

Table 5. Comparison of the smart home energy management system solutions developed in terms of system characteristics and elements improving the convenience of system use

Cost-Effective strategy	Comfort strategy
Solutions improving convenience of use	
Ability to remotely monitor and control home appliances using a mobile device or computer	Ability to remotely monitor and control home appliances using a mobile device, computer or LCD HMI screen
IoT device communication (operation messages, failure alerts, etc.)	System visualisation on the building map
Monitoring of electric energy consumption	IoT device communication (operation messages, failure alerts, etc.)
	Lighting control
	Temperature control
	Security management (smart locks, video intercom, presence sensors)
	Monitoring of energy consumption by the house in total, individual receivers, and the ability to disconnect receivers (running electric energy management)

An analysis of the convenience of using the electric installation for the two house solutions demonstrated that either installation improves its convenience. A common element improving user convenience is the ability to remotely control home appliances from a cloud-based application. This allows the users to control and monitor home appliances from any location. A solution based on the comfort strategy provides much higher user convenience through the use of numerous subsystems.

5. CONCLUSIONS

Multi-criterion analysis results for the two developed smart home energy management system solutions show that the combination of energy management system and renewable energy source brings material effects, providing energy savings of at least 11–31% [Horyński 2015], and when they are focused on a specific group of devices, an energy demand reduction of up to 60% can be achieved, although with a much lower convenience level. With a properly configured smart home energy management system (use of energy storage), independence from the external energy grid (zero-energy building) can also be achieved.

In both cases, the investment cost of building the energy management system and a renewable energy source in the form of a photovoltaic installation are substantial, the investor must factor in major initial financial expenditure, which pays back for itself over the years of installation operation by reducing the electric energy bills. The payback time of a solution based on a cost-effective strategy demonstrates the viability of such an installation. The format based on the convenience solution exhibits a high potential for energy savings, but the massive investment costs can also raise doubts as to the viability of its use, but if one’s aim is to maintain a high level of convenience, its use in this case is justified.

Installation of a smart home energy management system improves the home user’s convenience through various features, such as the ability to remotely control home appliances or systems from any location. Adopting the comfort strategy enables achieving a much higher level of system usage convenience, but adopting the opposite energy management direction in the smart home system, which is reducing the costs of energy purchasing, also has certain elements providing the users with a sense of convenience, although not as extensive as for the comfort strategy.

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