Frontiers in Energy Research

TYPE Perspective
PUBLISHED 12 January 2023
DOI 10.3389/fenrg.2022.1109997

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Energy Storage,
a section of the journal
Frontiers in Energy Research

RECEIVED 28 November 2022
ACCEPTED 28 December 2022
PUBLISHED 12 January 2023

CITATION
Greening B, Braunholtz-Speight T, Wood R and Freer M (2023), Batteries and beyond: Multi-vector energy storage as a tool to decarbonise energy services.
Front. Energy Res. 10:1109997.
doi: 10.3389/fenrg.2022.1109997

Batteries and beyond: Multi-vector energy storage as a tool to decarbonise energy services

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With the 2015 Paris Agreement pursuing efforts to limit global temperature increase to below 2°C above pre-industrial levels and the "energy trilemma" goals of energy security, energy equity and environmental sustainability, decarbonisation remains a priority across all of the United Kingdom (United Kingdom) energy system, not just electricity. Electricity and thermal energy storage technologies can offer a host of benefits across the energy value chain through the abilityS to capture, store and then release electricity or thermal energy over a period of time. These benefits include helping capture the full potential of renewable generation and providing services such as frequency response and reserve to Great Britain's (GB) electricity system. In addition, with the aforementioned climate targets in mind, energy storage can also play a role in facilitating the decarbonisation of other activities and sectors. Here we delve deeper into how energy storage technologies can contribute to both energy sector transformation and more broadly, decarbonisation. Furthermore, we discuss the importance of ensuring a technology-agnostic approach to the development of policy and regulation with relevance to energy storage. This ensures that storage technologies with significant potential to contribute to the 'energy trilemma' goals are not precluded from entering the market due to unfavourable policy and regulatory frameworks.

KEYWORDS

energy storage, decarbonisation, thermal storage, energy value chain, energy trilemma, battery storage

Introduction

The United Kingdom's electricity, heating and transport sectors are undergoing fundamental changes to decarbonise and achieve the ambitious, but necessary, targets to combat climate change. These targets include keeping the global temperature rise this century well below 2°C, above pre-industrial levels as set out by the 2015 Paris Agreement (UNFCCC, 2015) and the recently legislated target for net zero greenhouse gas emissions by 2050 in the United Kingdom (The Climate Change Act 2008, 2019). Similarly, Germany is targeting between a 90% and 95% reduction in greenhouse gas emissions on 1990 levels by 2050 (Federal Ministry of Economics and Technology and C.a.N.S, 2010), and it is expected that other countries will follow suit and adopt similar legally-binding targets.

Climate-related targets and falling capital costs have led to the proliferation of renewables in the electricity generation mix. For example, the share of renewable electricity generation in the United Kingdom was a record 39% in 2022, whilst circa 25% of heat generation came from renewable sources (UK Department of Business, E.a.I.S, 2019). There are also increasing numbers of Electric Vehicles (EVs) and National Grid forecast that there could be over

35 million EVs on the road in the United Kingdom by 2050 (Grid, 2019a). Globally, renewables' share of energy generation has been increasing, and many countries have set targets to take this trend further. For example, renewables were responsible for 24% of US electricity generation in 2022 (US Energy Information Administration, 2019), whilst European Union (EU) countries are already working towards renewables targets ranging from 10% to 49% of final energy consumption by 2020, in line with the Renewable Energy Directive (RED) (The European Parliament and The Council of the European Union, 2018).

Increasing renewable capacity is displacing traditional forms of fuel and generation in energy systems, which we consider to encompass electricity provision, heating (and cooling) and mobility in this article. Furthermore, the way in which energy is consumed is changing, with the once passive consumer becoming a 'prosumer' with their own source of generation and greater control over their energy consumption (e.g., *via* smart energy technology) (Good et al., 2017a). Consequently, new flexible solutions are required to deal with the challenges (e.g., intermittency, inflexibility) arising from these transformations while reducing greenhouse gas emissions (Zhang et al., 2017a).

Energy storage is one such solution to these challenges and it can offer a number of services to various users across the energy value chain (e.g., generators, network operators and consumers). In addition, in the drive to decarbonise certain sectors, a shift towards the electrification of heating and transport is underway, providing opportunities for energy storage to play a greater role in heating and mobility (Zhang et al., 20172017).

In this article, we discuss how a range of electricity and thermal energy storage technologies can facilitate decarbonisation in the United Kingdom (focusing on the options in development in the United Kingdom and including the less-market-ready options to avoid a potential technological lock-out), in addition to providing other beneficial services. We focus not only on its application in electricity generation but also on the role storage could play in the heating and transport sectors. We also discuss the need for policy and regulatory development to give all technologies an equal footing to compete.

Batteries and beyond

Electricity storage, particularly battery electricity storage, tends to take centre stage in discussions concerning energy storage, owing to the rapidly declining costs of lithium-ion battery technology (prices fell 73% between 2010 and 2016) (Curry, 2017). However, it is also important to consider other electricity storage technologies and thermal energy storage, as they can provide services that could benefit current and future energy systems. Table 1 details the main electricity and thermal energy storage technologies considered for energy storage in the United Kingdom.

Energy storage is expected to play an important role in the transition towards more sustainable energy systems in both the United Kingdom

TABLE 1 Energy storage technologies.

Technology (electricity/heat)	Type	Vector	Capacity	Duration	Cycles or lifetime	Efficiency	Response	System services
Pumped hydro storage	Mechanical	Electricity	100 s MW—GWs	Hours	>13,000 cycles 30–60 years	70–85%	Seconds to minutes	Meeting peak demand; spinning reserve; frequency regulation
Flywheels	Mechanical	Electricity	10 s kW—MWs	Seconds to minutes	>100,000 cycles	70–95%	Instantaneous	Onsite power; frequency and regulation
Compressed air energy storage (CAES)	Mechanical	Electricity	100MW–1 GW	Hours to days	>10,000 cycles 20–40 years	60–70%	Seconds to minutes	—
Liquid air (cryogenic) energy storage (LAES)	Chemical	Electricity	5MW–100 s MW	Hours to days	20–40 years	60–75%	Minutes	Non-spinning reserve, frequency regulation; transmission congestion relief; transmission support; voltage support
Conventional batteries (lead acid, lithium ion)	Electrochemical	Electricity	0.1–100 MW 1 kW–10 sMW	Minutes to hours	2,200 > 100,000 10,000–10,0000	75–95%	Milliseconds	Used for many years to provide UPS and storage in mini-grids and off-grid application; voltage control; frequency control; reserve services
High-temperature batteries (NAS, NaNiCl)	Electrochemical	Electricity	10–1000 MW	Minutes to hours	2,500–4,4000	70–90%	Milliseconds	—
Flow batteries (va redox, zinc bromine)	Electrochemical	Electricity	100 s kW—10 s MW	Hours	>10,000 cycles	60–85%	Milliseconds	Long-duration smoothing and load shifting
Power-to-Gas/ Hydrogen	Chemical	Electricity and/or heat	10 s MW—GWs	Hours to weeks	5–30 years	25–45%	Minutes	—
Hot water tanks and storage heaters	Thermal	Heat	—	Hours	15 years	c. 30%	Seconds to minutes	Heat buffer; smoothing peak heat demand

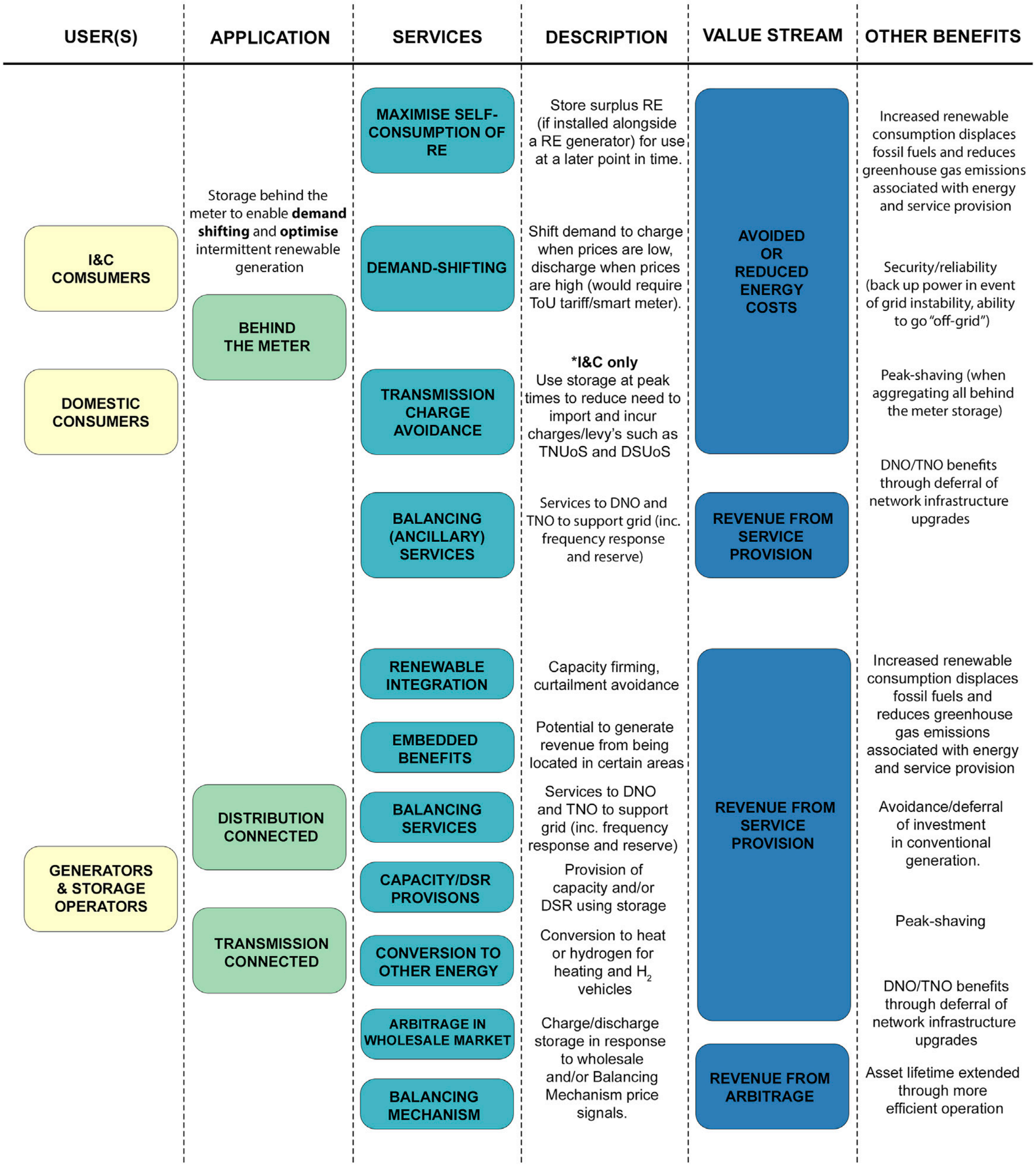

FIGURE 1
Energy storage users, applications and services.

and further afield. In the United Kingdom, National Grid's (NG) Future Energy Scenarios (FES) estimate that electricity storage capacity (excluding Vehicle-to-Grid capacity) could range from 14 Gigawatt (GW) ("Steady Progression" scenario) to 28 GW ("Community Renewables" scenario) by 2050, whilst 25% of homes are expected to possess thermal storage by 2050 in their "Net Zero" analysis (Grid, 2019a). In addition, as EVs become the dominant form of road transport, estimates of their potential storage capacity could contribute to the grid range from 7 GW to 20 GW by 2050 (Vivid Economics and Imperial College, 2018; Grid, 2019b). The Committee on Climate Change estimate that improvements in system flexibility could bring electricity system costs down by £3-8 billion/year by 2030 and £16 billion/year by 2050 (Committee on Climate Change, 2019).

The benefits associated with electricity and thermal energy storage are wide-ranging. MY-STORE work has found gains from connecting energy storage at all levels of the energy system: from co-location with transmission-connected generators, through use in district heating schemes, to behind-the-meter end-user installations. As a result, actors across the energy value chain (e.g., generators, network operators, end users) can all benefit from energy storage, as summarised in Figure 1. That said, distributed control of storage may be more efficient in terms of demands on computational control resources than centralised control, for example, to provide Enhanced Frequency Response services (Zhao et al., 2020). Modelling also suggests that community- or district-level management of an integrated multi-energy system, including thermal as well as electricity energy storage in individual buildings, can successfully ameliorate network constraints from the addition of new loads (such as electric heat pumps or electric vehicles) to the electricity system (Good and Mancarella, 2019).

The ability to store surplus renewable energy helps improve the integration of renewable generation into networks (e.g., capacity firming, curtailment avoidance), maximise self-consumption and shift demand to more favourable, lower cost periods. These benefits in turn can reduce energy-related costs, contribute to greater decarbonisation and unlock additional revenue streams (e.g., balancing services and arbitrage opportunities). Furthermore, energy storage is of value to network operators by enabling the deferral (or avoidance) of network infrastructure upgrades (as a cost-effective alternative) and providing grid stability services such as frequency response, reserve and reactive power (Good et al., 2017a; Clegg and Mancarella, 2019a).

The aforementioned benefits are commonly discussed when communicating the merits of battery storage. However, they are also applicable to other technologies. For example, the utilisation of thermal energy storage in conjunction with heat pumps can suppress peak electricity demand by charging during off-peak hours (Good and Mancarella, 2019). The multiple roles that coolth storage could play should also be considered, as they may be increasingly relevant in a warming climate. In certain cases, alternative technologies to batteries may offer greater benefits or be more suited to a given application, for example, offering longer duration storage to facilitate inter-seasonal storage, better scalability or faster response times to provide grid support services. Integrating storage technologies across energy vectors allows for a wider range of assets to be used to provide electricity system services and access revenue streams. For example, electrolysers at hydrogen refuelling stations not only allow renewable electricity to be used to power hydrogen vehicles but could also provide ancillary services to the electricity system, including fast frequency response, primary frequency response and secondary and tertiary reserves (Zhang et al., 2017b). Integrated multi-energy systems also facilitate the switching of the provision of an energy service to an alternative device/service (i.e., substitution) and can help avoid further capacity expansion (Good et al., 2017b; Clegg and Mancarella, 2019a). Energy storage can also give rise to other benefits relating to decarbonisation, which are not solely limited to the electricity generation sector. These will be discussed in detail in the following section.

Key to realising widespread deployment will be the ability to build a strong business case for storage that recoups investment costs and provides a return on investment. Crucial to this will be the development of new business models and products that allow storage owners to capture the multiple sources of value that storage can tap into (known as "revenue stacking") (Good et al., 2017a; Zhang et al., 2017a; Good and Mancarella, 2019). However, in some cases the revenues from multiple services are not additive, since certain services will require the system to be available during specific time windows solely to provide that service, thus ruling them out of participating in the provision of other services. Furthermore, a major challenge being faced today is that markets for storage are either difficult to access, not very well developed for storage, or do not even exist yet. Changes to market rules and regulatory frameworks are expected to help improve the markets for storage. However, for the time being, uncertainty remains which could discourage positive investment decisions. Currently, storage owners will rely upon a combination of revenues from the wholesale market (and balancing mechanism), grid balancing services (such as frequency response) and the capacity market.

Energy storage as an enabler for decarbonisation

As briefly touched upon earlier in this article, in response to recommendations by the Committee on Climate Change (CCC), the United Kingdom government has recently passed legislation setting out a new emissions target for the United Kingdom in order to fully meet its obligations under the Paris Agreement (The Climate Change Act 2008, 2019). While previously, the United Kingdom aimed for an 80% reduction in greenhouse gases from 1990 levels by 2050, the new target is to reach net-zero greenhouse gas emissions by 2050. Energy storage can assist in achieving this target, but it is important with the tight, physical interactions and synergies that exist across electricity, heating, cooling and mobility to consider the decarbonisation potential of storage in a multi-energy system context (Good et al., 2017a; Clegg and Mancarella, 2019a; Clegg and Mancarella, 2019b). This is particularly important given that the energy supply and transport sectors were responsible for 24% and 27% of the United Kingdom's greenhouse gas emissions, respectively, in 2017 (UK Department of Business, E.a.I.S, 2017, 2019). In addition, residential and public sectors are responsible for circa 16% of overall greenhouse gas emissions, predominantly due to the combustion of fuels for heating purposes.

Energy storage can facilitate greater decarbonisation by maximising the self-consumption of renewable energy through storing surplus renewable generation for use later in time. This will lead to the greater displacement of conventional fossil fuel generation, thus reducing greenhouse gas emissions whilst also reducing the curtailment of renewable generation by storing temporary surplus energy production and increasing energy flexibility. Storage can not only displace conventional generation in the form of energy supply but also by displacing conventional generation in the provision of grid support services (i.e., ancillary services). This includes providing reserve capacity and frequency response services. Certain grid-connected technologies, such as LAES, can also provide black-start capabilities.

Work from the MY-STORE project compared the life cycle of Carbon Dioxide (CO_2) emissions associated with a solar Photovoltaic (PV) plus battery storage system installed in a medium-sized non-domestic building in the United Kingdom with those associated with using grid electricity over a 30 years lifetime (Jones et al., 2017). It was established that the solar plus battery system could reduce the building's CO_2 emissions by 17% compared to the grid-only reference. Another MY-STORE study showed how a system comprising of an electric heat pump and a domestic hot water storage tank could be utilised to provide flexibility to the electricity grid in the form of Demand Side Response (DSR) by increasing or reducing heat pump demand in response to price signals (Zhang et al., 20172017). This has multiple benefits. It reduces electricity system stress, and users' energy costs, by shifting heat pump demand to lower-cost periods, where water can be heated for storage and subsequent use during high-cost periods. Importantly, this also reduces the emissions associated with providing heating and electricity grid support services by displacing conventional fossil fuel generation that would typically provide these services.

Other technologies can also help decarbonise across sectors. Electrolysers can do this by varying their output in line with renewable energy generation and electricity system requirements, which reduces the requirement for conventional fossil fuel generation (e.g., CCGTs) to be online, thus reducing the carbon intensity as the provision of services shifts from conventional to power-to-gas (Zhang et al., 2017b). For example, they will consume electricity when supply exceeds demand and reduce electricity demand (partially or completely) when demand exceeds supply, and the deployment of hybrid heating systems could switch to use gas in place of electricity as the fuel source, thereby reducing the need for more expensive peaking plants resulting in a 24% reduction in peak conventional generation (Clegg and Mancarella, 2019a). Applications of electrolysers could include on the Distribution Network (DN) and at vehicle refuelling stations. At refuelling stations, they could be installed alongside hydrogen storage to convert renewable energy (wind, solar) to hydrogen (Zhang et al., 2017b). The produced hydrogen could then be stored prior to use in vehicles. MY-STORE work presented a model to assess how the power system can help decarbonise the transportation sector and how refuelling stations can contribute to power system reserves. It demonstrated how hydrogen storage plus electrolysers at a vehicle refuelling station could both provide fuel for vehicles and power system ancillary services, which leads to a 60.5% reduction in the carbon intensity of the power sector, and if electrolysers were used for frequency control ancillary services, they could provide 44% of primary frequency response, 7% of secondary reserves and 0.2% of tertiary reserves (Clegg et al., 2017). It therefore has a mutual benefit in the form of decarbonisation of both the power and mobility sectors.

Comparison of different storage technologies to one another and to traditional technologies is important to maximise decarbonisation gains. For example, storage is always preferable on environmental terms compared to the use of diesel and OCGT, based on per MW output to the grid. However, a Life Cycle Analysis approach shows that storage technologies with volume scaling benefits and greater recyclability—such as LAES and redox flow batteries—can provide greater environmental benefits compared to modular systems such as Li-ion batteries (Jones et al., 2020).

Conclusions: challenges for policy and regulatory development

Efforts have been directed towards removing the associated barriers, including legally defining electricity storage, ensuring it is charged fairly and developing markets and products to fully value the services storage can provide (to enable strong business cases to be built). This is evident in the United Kingdom government and Ofgem's "Smart Systems and Flexibility Plan", where most of the actions put forward are focused on the application of storage within electricity networks and markets (UK Department of Business and Ofgem, 2017; UK Department of Business and Ofgem, 2018). Similarly, government funding has predominantly gone to electricity storage, particularly battery technologies. For example, a MY-STORE review of the demonstration project funded by the Low Carbon Networks Fund (LCNF) found that most of the projects were battery storage technologies, which raises questions about support for other technologies that are less market-ready. The Supplementary Figure S1 shows a timeline of energy storage policy and regulatory development in the United Kingdom since 2015. It shows that the focus to date by BEIS, National Grid and Ofgem has been heavily weighted towards electricity energy storage and its application within electricity systems. Future research and collaboration with industry and governments will be required to further action towards non-electricity based energy storage (such as power-to-gas, hot water tanks and geological hydrogen storage) to determine their deployment potentials and applications within energy systems for the United Kingdom and abroad.

MY-STORE research has emphasised that broader and clearer policy, regulatory, costing and safety frameworks that encompass thermal energy storage and consider both existing and emerging energy storage technologies are required to realise the full benefits of storage. This will ensure that markets and regulations are sufficiently flexible to enable solutions that are not yet market-ready or in earlier stages of development to enter the market at a future time. As emphasised in the previous section, a multi-energy system view will be key to this holistic approach to energy storage (Good et al., 2017a; Clegg and Mancarella, 2019a). It will also be important to consider how storage capacity could be increased through co-deployment with other emerging technologies, for example, installing energy storage alongside a solar PV system or in conjunction with electric vehicles and DSR.

In addition, it is important to review a wide range of metrics when evaluating energy storage technologies, particularly the life cycle environmental impacts, given the strong focus on decarbonisation as set out by the United Kingdom's recently amended climate change targets (Jones et al., 2020). The environmental performance of storage systems is strongly influenced by energy and material inputs to manufacturing, product life span, recyclability and round-trip efficiency. Comparisons of storage solutions should therefore look beyond round-trip efficiency when assessing storage performance. MY-STORE work showed that when taking a Life Cycle Assessment (LCA) approach that redox flow batteries and LAES provide both recyclability and scalability benefits over Li-ion batteries, and these benefits translate into broader environmental benefits (Jones et al., 2020). Future research through further tailored life cycle and techno-economic assessments will be required to determine the deployment, sustainability and system integration potential for each energy storage option on a case-by-case and place-by-place basis.

The overarching conclusion to this research is that viewing energy storage as purely battery technologies will miss a number of wider opportunities that other energy storage solutions (electrical and thermal) can provide in the transition to more decarbonised energy systems across power, heating, cooling and mobility. This is not to say batteries will not play an integral part in current and future energy systems. However, given that other technologies can offer similar benefits and services in addition to their cross-sector decarbonisation potential, they should be considered alongside batteries in developing markets, policies and regulatory frameworks. The inherent risk in not doing this is that the less developed or market-ready technologies could be locked out, resulting in lost opportunities to accelerate decarbonisation across energy systems and achieve climate change targets.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

BG, TB-S and RW performed the statistical analysis, and wrote the first draft of the manuscript. All Authors wrote sections of the manuscript. BG, TB-S and RW authors contributed to conception and design of the study contributed and all authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was funded by EPSRC within the project PUrE Intrawise (Grant no. EP/F007132/1).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.1109997/full#supplementary-material

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