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Smart management for integrated energy systems: tools from communities to regions

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Abstract:

The novel concept of Smart Energy Systems has emerged over the last decade within the context of the energy transition toward a carbon-free sustainable future. For an energy system to be “smart”, several factors have to converge: (i) a high integration of renewable energy sources, (ii) the flexibility required to deal with their fluctuating nature, (iii) the exploitation of digital technologies and (iv) the cross-sectoral approach that uses synergies between various energy domains (sector coupling). Indeed, the traditional domain-specific energy flows from production to usage are overcome in favor of an integrated approach, in which energy is converted or stored into the most convenient vector. Coupling energy sectors, however, requires smart management and control strategies that are able to drive a system toward minimal energy use (or minimal cost), despite its increased complexity. Furthermore, the advanced management strategy of a smart energy system may vary significantly depending on its spatial dimensions, from the national/regional level to small-scale energy communities or islands. Hence, pointing out the latest progress on smart management is paramount for orienting future research and practice, and fostering the energy transition. This work reviews the available methods and tools for enabling the optimal operation of smart energy systems at different spatial and temporal scales. They are categorized according to relevant features such as the energy vectors and infrastructures involved, the presence of short-term or seasonal storage, the time horizon and specific application. The paper also summarizes research guidelines and drivers for the continuous development and expansion of smart energy systems at all levels. It was found particularly relevant to investigate optimal management at multiple time and space scales at the same time, for exploiting not only synergies between sectors, but also between neighboring communities. The tools should also have the possibility to include additional energy vectors (e.g. different types of chemicals) and their verification in demonstration cases should be promoted.

Keywords:

Control; Hybrid energy systems; Modeling; Optimization; Sector coupling; Smart energy systems; Smart management; System integration.

1. Introduction

Over the last few decades, the decarbonization of all human activities has become a global priority recognized by the international scientific community. Reducing greenhouse gas emissions is indeed a fundamental step to mitigate the effects of human activities on the climate and environment. Being one of the most carbon-intensive areas, the energy sector offers significant room for improvement. To this end, researchers have devoted great efforts in investigating and developing new concepts for the energy sector of the future [1].

In this context, the necessary steps to take are the implementation of energy efficiency actions, and the more rational exploitation of available resources and fuels. Hence, the energy system is progressively undergoing a transition toward a new paradigm, also referred to as sector coupling [2]. This indicates the interconnection between different sectors achieved by integrating multiple energy carriers and exploiting their synergies to enhance overall conversion efficiency. A system with these features is often regarded as an Integrated Energy System (IES) and is shown in Figure 1.

The very first example of this concept was the combined production of heat and electricity within a single plant, i.e. cogeneration unit. This is a high efficiency technology that recovers heat otherwise lost in the environment. Additional steps have been taken with the electrification of heat production and the transport sector.

The rise of new technologies and the possibility to exploit unconventional energy carriers (such as synthetic fuels and chemicals) has led to the integration and interconnection of all energy sectors in a unique circular framework, from the production of electricity to heat at different temperature levels, and even to mobility. While the traditional shape of a generic energy system comprised linear energy flows that were sent from the source directly to the final use, in the new framework the energy flows extracted from the sources can undergo multiple

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passages before being used [3]. Some examples of these passages that characterize an IES are 1) conversion into a more cost-effective energy form, 2) accumulation into a storage device, and 3) supply into a distribution network.

The advantages of this new concept, compared to the previous one, are determinant:

- The cross-sectoral approach exploits the synergies between energy domains, so that energy can be transferred in the most convenient form depending on the specific conditions. For example, thermal demand can be translated into electrical demand by means of heat pumps. The deriving heat can be stored (more easily than electricity) or injected into heat distribution infrastructures for supplying entire communities. In parallel, excess electricity (e.g. from renewable sources) can also be converted into a chemical vector through Power-To-Gas systems, to be used at a later time or in a different location.
- An IES presents more degrees of freedom thanks to the different operation possibilities descending from the previous points, thus providing sufficient flexibility to deal with varying conditions.
- The higher flexibility, in turn, makes it possible to reduce the risk of curtailment of non-programmable renewable energy sources, and to operate programmable plants in a more profitable operating range.
- The available local resources can be put at the disposal of a larger community, so that energy can be produced and self-consumed locally, reducing grid losses. An example of this is the constitution of Renewable Energy Communities (REC), according to the recent European legislation.

Although this growing interconnection represents a key part of the energy transition due to the aforementioned benefits, it determines new challenges that deserve to be addressed. The most crucial is that the profitable layout and operation of a given system does not depend only on the single user or single plant, but is highly influenced by the neighboring users and entire infrastructure, including all connected elements and networks.

In this sense, IESs have to become Smart Energy Systems (SES), the definition of which is not limited to the co-operation of different energy infrastructures. A key feature of a SES is that it is planned, designed, operated, or optimized with the aid of dedicated digital tools. In more detail, tools for smart management are particularly relevant for dealing automatically with the complexity of the new paradigm. Indeed, they eliminate the risk of bad operations and relieve operators and technicians from the duty of locally controlling the energy flows of a complex new system for which neither expertise nor data are available.

Until recent years, major efforts have been directed toward the optimization of the electricity sector at all levels, as in the case of REC. Nonetheless, as shown above, the greatest benefits can be enabled by integrating all sectors, especially heat which constitutes at least half of the final energy use in Europe. A recent paper summarizes the development tools for the plant design and control of electro-thermal systems [4]: a system-level framework for the modeling, control, and design of multi-domain systems is defined, with a list of control methods as well as implementation tools (e.g. software and toolboxes). However, the focus is limited to future electrified vehicles. Similarly, Mishra et al. [5] review the technologies for sizing and operating innovative control in renewable integrated energy systems, with the sole focus on stand-alone and grid-connected electricity systems. Here, the term “integrated” is adopted to define an electricity-based system including a wide range of renewable technologies.

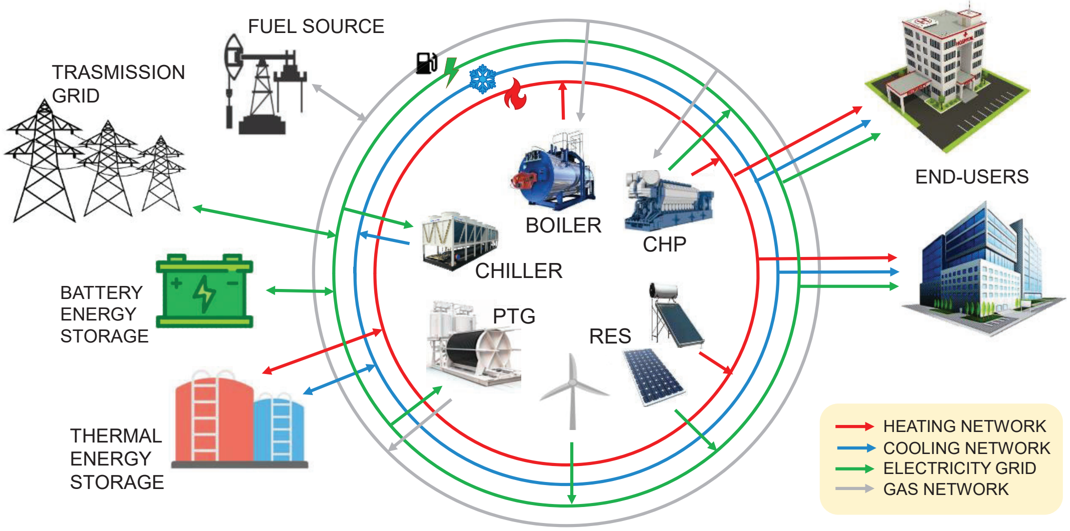

Figure. 1. An example of an integrated energy system in the framework of sector coupling with the electricity, heating, cooling and gas infrastructures. CHP: Combined Heat and Power plant, RES: Renewable Energy Sources, PTG: Power-To-Gas.

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Whilst purely electrical infrastructures often have similar features in terms of time scale, due to their very fast dynamics, when coupling different sectors, the differences in time dynamics should be carefully investigated, and also considered in the related optimization tool. In addition, an IES can be implemented in different spatial dimensions, ranging from the IES for an individual building, to its community-scale application, to the whole national energy system of a country. When communities and networks are concerned, there are also large differences in system layouts and network topology.

All these aspects make the development of tools for IES smart management challenging but also critical for the energy transition. Indeed, it is firstly determinant to choose the appropriate tool, algorithm or methodology depending on the desired time or space scale, or even depending on the specific application. Since sector coupling and IES investigation is a rather novel topic, the state-of-the-art research does not offer a detailed overview of these tools. Despite the fact that tools for IES simulation and modeling have been surveyed in [6], to the best of the authors' knowledge, no unique set of tools for smart management exists in the literature.

This paper aims to provide a catalogue of the most recent works that presents tools for optimization and management of IES in the perspective of sector coupling. A particular distinction is made regarding the spatial dimension and time horizon in which each selected tool is supposed to be applied, or offers the greatest benefits. This analysis includes a thorough review of the literature, the selection of the most relevant papers for this purpose, and the extraction of the features of the proposed tools. To restrict the research field, this review aims to give an answer to the following research questions:

- How can smart management be applied to integrated energy systems at different spatial levels?
- Which are the tools that can enable system planning, design, optimization and management when considering different time horizons?

Finally, a set of drivers and guidelines based on the obtained results are given as indications for future research in the field.

2. The concept of sector coupling

2.1. Definition

It can be seen from the literature that a clear contextualization of sector coupling is missing. As noted by Ramsebner et al. [2], the term is often misinterpreted: it is used in a wide range of cases, from the bare inclusion of renewable energy sources, to the coupling of the production of energy and transportation. By contrast, if the scope is restricted to the field of energy production, distribution and utilization, available sources and research works adopt different terms to define the same concept (IES, in the scope of this research).

The focus of this paper is to produce an overview of the tools to achieve the optimal management of IES in the framework of sector coupling. This task is therefore subordinated to the preliminary identification and explanation of the terms used in the literature to refer to IES (as in the meaning given in Section 1). These definitions, which are detailed in Table 1, also represent the main keywords used in the literature search.

With reference to the term "hybrid energy systems" [7], it is worth specifying that, apart from the scope of sector coupling, the term can also identify the following concepts:

- A system in which different conversion units are integrated to pursue the same scope (e.g. supplying electricity). This is the case of renewable energy sources coupled with conventional power plants.
- A system in which different components are integrated within the same power plant to enhance plant efficiency (e.g. fuel cells coupled with gas turbines).

Hence, when analyzing the literature and selecting relevant papers as well as the related tools, particular attention has to be paid to this term.

2.2. Infrastructures

The whole energy system is based on infrastructures that can connect the energy conversion systems with users or storage devices at different scales. These infrastructures are shaped as networks that may have different topologies according to the specific domain. In particular, it is worth mentioning electrical grids, natural gas networks, and heating and cooling networks [8].

Electrical energy and natural gas can be transferred for long distances and then distributed in a widespread manner to the single users. Therefore, in general, these networks are structured with transmission networks (e.g. at high voltage or pressure in order to reduce dissipation) and distribution networks (e.g. where voltage and pressure are progressively decreased toward the users).

Conversely, heat cannot be efficiently transported for more than a few kilometers. Therefore, its production must be close to the users and the networks are only for its distribution. Another peculiarity of heating and cooling networks is that they use a medium for heat distribution (e.g. steam or water) and, therefore, they are composed of supply and return piping.

All these infrastructures were traditionally intended as passive and one-directional, with the energy transferred from a small amount of source points (e.g. power plants) to a high number of sink points (e.g. houses and

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factories). Starting from the electrical grid they are becoming progressively more active and bi-directional with an increase in the number of production points and the presence of points that can alternatively be a source or a sink (i.e. the so-called prosumers).

Storage technologies [1] are a key part of the infrastructures, and have become more relevant over the past decades to decouple energy production (often deriving from discontinuous or uncontrollable sources) from its utilization. From the temporal perspective, in this paper the storage technologies are grouped into two categories:

- Short-term storage: this kind of storage technology is characterized by high power but low capacity and therefore it can act over time scales up to one day. It includes, for example, flywheels, batteries and thermal energy storage tanks.
- Long-term storage: this kind of storage technology is characterized by high power and high capacity and can act over time scales from days to months. It comprises, for example, flow batteries, pumped hydro, compressed air, chemicals, seasonal heat storage (e.g. pit thermal energy storage).

Besides the aforementioned energy networks, there is another energy distribution infrastructure, that was traditionally considered disconnected, but which is becoming progressively integrated: fuel for transportation.

2.3. Coupling technologies

Within an IES, the infrastructures described above are connected by means of coupling technologies, which can also be defined as bridging technologies. They are energy conversion units that convert an energy vector into one or more different energy vectors.

Conventional coupling technologies are (i) boilers (i.e. from fuels to heat); (ii) engines (coupled with alternators), which when configurated as cogeneration units can bridge the fuel domain with both the electrical energy and heat domains; and (iii) chillers (i.e. from electrical energy to cooling energy).

The most innovative technologies are heat pumps [1] and Power-To-Gas (PTG). Heat pumps are based on the same working principle of the electric chillers, but in heat pumps the output is the heat that it is delivered at high temperature. Heat pumps can work in a reversible way (i.e. using the electricity to produce heat in winter time and cooling energy in summer time) or they can also have a double effect (i.e. the production of both a cold and warm vector at the same time).

PTG refers to a technology that converts electrical energy into a gaseous fuel (e.g hydrogen or methane). It is therefore composed of an electrolyzer that produces a hydrogen stream, which can be stored or combined with a carbon dioxide stream to feed a reactor for their conversion into methane and water. The water can be removed by condensing it and the methane can be stored or injected into the network.

Table 1. Terms used in the literature to identify integrated energy systems in the context of sector coupling.

Name	Detailed explanation	References
Sector coupling	"The concept of SC encompasses co-production, combined use, conversion, and substitution of different energy supply and demand forms—electricity, heat, and fuels"	[9]
Integrated energy systems	"(IES) combine on-site power generation technologies with technologies for heating and cooling" and "bring together all forms of cooling, heating and power […] combined heat and power […], and cogeneration technologies."	[10]
Multi-energy systems	"A system designed to allow the operator to choose between multiple energy sources"; and also systems "whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other at various levels"	[3,11]
Hybrid energy systems	"Hybrid energy systems are combinations of two or more energy conversion devices (e.g. electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either."	[7]
Energy hub	"A unit where multiple energy carriers can be converted, conditioned and stored. It represents an interface between different energy infrastructures and/or loads"	[12]
Smart energy systems	"an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allows for the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions"	[8]

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By broadening the focus also to the transportation sector, charging infrastructure for electric vehicles can be considered as a bridging technology. It is worth mentioning that this coupling can also enable storage technologies such as Vehicle-to-Grid. This involves batteries of electric vehicles connected to charging stations being provisionally at the disposal of the power grid as storage to aid its operation.

3. Methodology

The methodology adopted to carry out the investigation in this work involved a thorough search of the current scientific literature concerning the subject of integrated energy systems in the framework defined in Section 2.1. The search in international scientific databases was conducted with a combination of keywords to identify both the subject and specific aim of each work. To this end, the keywords defined in Table 1 were in turn combined with keywords such as “optimization”, “control”, “management” and “operation”, in order to restrict the analysis to smart management tools.

Since sector coupling has become a broad topic over the last few years, and research papers have been growing continuously since the first definition, the output of this search was filtered adopting the following criteria for inclusion in the review:

- the paper covers a system with at least two energy vectors or networks;
- the paper presents a novel tool for the design, optimization or management of an IES;
- the spatial scale in which the proposed tool is applied is clearly identified within the scope of the paper;
- the time framework (e.g. time discretization, time horizon) for the application of the proposed tool is clearly determined.

The last two points are particularly relevant to this review. Indeed, the aim of this investigation is to classify the innovative methods and tools that allow an IES to be analyzed and optimized considering the differences that derive from the spatial and temporal dimensions.

To achieve this goal, the selected papers were thoroughly examined to extract their relevant features related to: (i) energy vectors tackled by the proposed tool; (ii) space and time scales; (iii) the presence of storage; (iv) the main aim of the tool; and (v) specific notes on the algorithms or software packages used. In addition, geographical and technical details on the case studies, if present, are noted. The features, divided into categories, are explained in Table 2.

Finally, the deriving information was collected in a broad table that presents an overview of the available studies, in order to:

- View the characteristics of each selected paper;
- Make comparisons between the presented tools;
- Understand which are the most covered aspects and, by contrast, the major gaps that should be tackled by future research;
- Verify if there are tools that tackle more than one feature at the same time, with reference to the same category.

Table 2. Features for the categorization of the selected papers.

Category	Features	Description
Energy vectors	Electricity, heating, cooling, natural gas, hydrogen, steam, other fuels, transportation*	The energy vectors comprised in the IES or included in the tool
Spatial scale	Building, community, city, region, nation or greater (Europe)	The spatial scale of application of the tool, ranging from individual buildings to systems spanning different nations
Time scale	Hours, days, weeks, year, or even multiple years	The time horizon for the investigation performed by the tool
Time discretization	Quarter hours or smaller, hour, day	The time-step for subdivision of the time scale of the tool
Storage	Short-term, long-term	The tool or application considers one or more types of storage, specifying its time scale
Aim of the tool	Simulation, optimization, management, design, long-term planning	Specific aim or aims of the tool (management is related to operation scheduling as well as real-time control)
Algorithms	-	If relevant, this field defines the existing algorithms or software used
Case study	-	If relevant, this field collects the main technical and geographical information of the case studies presented as applications

*Despite being a sector and not an energy vector, transportation was added to consider the aspects of mobility that can be integrated into a broader energy system (e.g. electric vehicles).

It is particularly relevant to consider the last point because, with the growing expansion of IES with different characteristics, it will be necessary to use versatile and multi-scale methods, and not just case-dependent tools that are tailored to a single application. The table of papers obtained in this review makes it possible to identify multi-scale studies (either spatial or temporal) and to verify where room for improvement can be found.

4. Results

The results of the investigation carried out in this work (and outlined in Section 3) are reported in Table 3, which lists the selected papers and the specific features of the proposed tools for the optimal design and operation of IES. The table aims to provide a basis for 1) making comparisons between methods, 2) selecting the most adequate method for a given application, and 3) understanding research gaps and drivers for the future. All these tasks are relevant to the expanding research field of IES.

Overall, 34 papers were selected for the scope of this analysis (and for the sake of space limitations), 4 of which were published before 2020 while the other 30 were published between 2020 and 2023. This distribution reflects the fact that, from the first definitions of sector coupling and IES in the mid 2000s, the number of works has dramatically increased over the last few years. However, it should not be concluded that, before 2020, researchers were not investigating these concepts. This literature search was conducted with precisely identified keywords, most of which were specified quite recently, and broadly adopted by researchers even more recently. Thus, most likely, the tools and methods proposed at earlier times were not labelled with the same definition. In addition, this literature search, which does not presume to be exhaustive, gave priority to more recent works, in order to delineate the latest tools available.

Various useful comments can be drawn from this overview:

- The sectors that are taken into consideration by the most part of papers are electricity, heating (sometimes coupled with cooling in district heating and cooling networks), and natural gas. These infrastructures are indeed the most advanced in current energy systems. However, it is expected that in the future other fuels (e.g. hydrogen, methanol and other non-conventional chemicals) will be an important part of an IES. This highlights a gap that deserves investigation.
- With regard to the building scale, it is common to only consider electricity and heating or cooling, i.e. the vectors that can be distributed internally, while few papers consider natural gas.
- On the contrary, at the scale of a wide region or an entire country, it is more common to include different types of fuels, whereas the aim of the analyses is mainly the optimal planning of capacity development in long-term scenarios (up to 2050). Real-time optimal management of PTG technologies was not found within the scope of this research.
- As already noted, large spatial scales are mainly devoted to simulating the system for future years, planning their development, or determining the optimal capacity and combination of sources for the considered area. In such cases, the time horizon for optimization is at least one year, but the management (with such a long time perspective) is carried out with typical days or typical weeks in the year. Thus, it is not representative of a real-time management tool.
- Investigations at community level are widespread, where community is often viewed as a district with a multiplicity of end-users, but it can also be seen as a set of coordinated power plants feeding a non-specified end-use. Particular attention should be paid to the end-use of each application. In any case, the community is equally analyzed with short time-scales (in the range of days, with the purpose of determining, in the best case, optimal control of the IES) or long time-scales (to schedule the operation of the system over an operating year).
- Storage technologies are almost always taken into consideration, since they enable flexibility and allow the full exploitation of optimal management, planning or design tools. Nevertheless, seasonal storage can be included in very few available tools, and only for those that view a relatively long time horizon.
- Overall, modeling and optimizing all energy sectors with fine discretization in terms of space and time can be computationally demanding. A feasible possibility is to increase the size of the time-steps or to select a few representative periods [13]. This strategy, however, can lead to biases in the generated optimal (or sub-optimal) solution.

An additional result of this research is the in-depth analysis of a selection of tools for each spatial scale, enriched with details on algorithms and case studies, where present. This is reported in Table 4.

It can be noted that a widely used method when dealing with optimal management at building and community scales is Model Predictive Control (MPC), which is an advanced control strategy that requires a model of the system. This feature, promising for the good performance of the management strategy, may make the problem intractable when the number of variables of the system grows. In general, the MILP formulation, a deterministic method that guarantees optimality, is the most used. For larger spatial scales, energy system models and sets of simulations with sensitivity analysis are used to deal with an increase in decision variables.

In light of the above, more studies and systematic reviews will be necessary to further outline the existing bibliography, and to investigate the links and relationship between all the presented features.

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Table 3. Relevant features of the tools proposed in the selected papers. E: electricity, H: heating, C: cooling, S: steam, NG: natural gas, H2: hydrogen, OC: other chemicals, M: mobility. ST: short-term, LT: long-term. Sim: simulation, Opt: optimization, Mng: management, Des: design/sizing, Pln: long-term planning.

Paper	Energy vector								Spatial scale	Time scale	Time discretization	Storage		Aim				
	E	H	C	S	NG	H2	OC	M				ST	LT	Sim	Opt	Mng	Des	Pln
[14]	✓	✓	✓		✓				building	hours + day	15 min + 1 h	✓			✓	✓		
[15]	✓	✓	✓						building	days	1 h	✓		✓		✓		
[16]	✓	✓							building	hours	-	✓			✓	✓		
[17]	✓	✓	✓						building	hours + day	1 h	✓			✓	✓		
[18]		✓	✓						building	year	1 h	✓	✓				✓	
[19]	✓	✓	✓						building, community	hours + day	1 h	✓			✓	✓		
[20]	✓	✓	✓						building, community	week	15 min	✓			✓	✓		
[21]	✓	✓	✓	✓	✓				building, community	days + year	15 min + 1 day	✓	✓	✓	✓	✓		
[22]	✓	✓	✓	✓					community	day	1 h	✓			✓	✓		
[23]	✓	✓	✓	✓					community	week + year	1 h	✓			✓	✓		
[13]	✓	✓	✓						community	day + year	15 min	✓			✓	✓	✓	
[24]	✓	✓			✓				community	day	15 min	✓			✓	✓		
[25]	✓	✓	✓						community	week + year	-	✓		✓		✓		
[26]	✓	✓			✓				community	hours + day	1 h	✓			✓	✓		
[27]	✓	✓	✓					✓	community	year	1 h	✓			✓			
[28]	✓	✓				✓			community	day	1 h	✓			✓	✓		
[29]	✓	✓			✓				community	hours + day	mins + 1 hour	✓						
[30]	✓	✓	✓		✓				community	day	1 h	✓			✓	✓		
[31]	✓	✓	✓		✓				community	hours + day	15 min	✓			✓	✓		
[32]	✓	✓							community	hours	15 min	✓			✓	✓	✓	
[33]	✓	✓	✓					✓	community, city	year	1 h	✓					✓	
[34]	✓	✓							community, city	day	15 min	✓			✓	✓		

Paper	Energy vector								Spatial scale	Time scale	Time discretization	Storage		Aim				
	E	H	C	S	NG	H2	OC	M				ST	LT	Sim	Opt	Mng	Des	Pln
[35]	✓	✓	✓		✓	✓			community, city	day	15 min	✓			✓	✓		
[36]	✓	✓						✓	city	year	1 h	✓			✓	✓	✓	
[37]	✓	✓	✓		✓				region	day	1 h				✓	✓		
[38]	✓								region	day	1 h	✓	✓			✓		
[39]	✓	✓						✓	nation	year	1 h	✓		✓	✓		✓	
[40]	✓	✓							nation	-	1 h + 1 day	✓			✓		✓	✓
[41]	✓	✓			✓		✓	✓	nation	multiple years	1 h	✓	✓		✓			✓
[42]	✓	✓							nation	multiple years	1 h	✓			✓			✓
[43]	✓				✓	✓	✓		nation	year	1 h	✓	✓	✓				✓
[44]	✓	✓					✓	✓	nation	multiple years	1 h	✓		✓	✓			
[45]	✓	✓	✓					✓	Europe	week + year	1 h	✓	✓	✓	✓	✓		
[46]	✓	✓				✓		✓	Europe	multiple years	1 h	✓	✓		✓	✓		✓

Table 4. Selected tools for different spatial scales with details regarding algorithms, software and case studies.

Spatial scale	Tool	Case study	Algorithm details
Building	**[17]** Economic MPC with three time scales: (i) scheduling of the next 24 h, (ii) real-time optimization of the next few hours and (iii) set-point tracking	An IES comprising RES, a gas turbine, electric and absorption chillers, a fuel cell, storages	Optimization problems solved in Python based on CasADi (IPOPT and BONMIN solvers)
	[20] MILP scheduling problem for a week, with evaluation of the thermal capacity of building as storage	1) a single building and 2) a university campus in northern Italy, with different IES designs	Optimization formulated with Pyomo and MILP solved with Gurobi solver
Community	**[13]** A two-level optimization: (i) Genetic Algorithm for determining demand side management actions and (ii) storage sizing + IES scheduling with LP	A district multi-energy system with tens of buildings	Optimization formulated and solved with MATLAB (Global Optimization Toolbox)
	[21] MPC with two time scales: (i) yearly scheduling updated every day to consider long-term effects and (ii) real-time unit commitment updated every 15 min	The IES of a hospital in Ferrara (Italy), including its district heating and cooling network	Optimization formulated and solved with MATLAB (Global Optimization Toolbox)
	[25] Multi-model dynamic simulation of the system and sensitivity analysis with different control strategies	A fifth-generation district heating network in Zurich, Switzerland	Model and simulation in IDA ICE
City	**[36]** Linear optimization model considering investment and dispatch within the electricity and heating sector	City of Gothenburg, Sweden, with the addition of electric cars and buses	City Energy Optimization Model
Nation	**[40]** Dispatch sector coupling model for optimal design minimizing energy system costs	The Swiss energy system	Open-source GRIMSEL-AH model
	[42] Balmorel energy system model (assuming a regime of 24 h a day, three days a week, seven representative weeks per year)	Scandinavian countries	Problem formulated in GAMS and solved with CPLEX solver (with great computation effort)
	[45] Soft linking of two models: (i) long-term planning multi-sectorial model and (ii) unit commitment and optimal dispatch model	The European energy system	JRC-EU-TIMES and Dispa-SET (solved with MILP formulation)

From this outline, it is also possible to derive research gaps that should be addressed to improve the smart management of future IES. Three significant drivers for further research are listed below:

- Optimal management of IES is generally tackled with a short time horizon, whereas it should be carried out with more than one time scale, one of which of the order of magnitude of months (up to one year). In this way, the IES control systems are able to account for the effects of long-term storage, large distribution networks and, most of all, storage into chemicals through PTG.
- Optimal management of IES is generally carried out at community level, by means of deterministic optimization algorithms that are subject to a drastic increase in computational time when the size of the system or the number of plants increase. Sector coupling implies indeed that all systems are always connected to neighboring areas. A potential solution to this issue is the decomposition of the problem into communicating sub-problems, each related to a spatial dimension. For this reason, research should focus on tools that consider more than one spatial level and can be implemented with similar features from buildings to wider regions.
- Most available tools for smart management are still at low levels of market readiness, as they are generally demonstrated with simulations or sensitivity analysis. Despite being challenging due to system size, it would be relevant to bring the proposed solutions to demonstration in an operational environment, in order to foster their uptake and see an actual impact on real systems.
- The use of hydrogen and other synthetic fuels produced by surplus electricity should be a determinant part of smart management tools, especially in the perspective of increasing the energy contribution from non-programmable RES.

5. Conclusions

Integrated Energy Systems (IES) have emerged over the last decade within the context of the energy transition toward a carbon-free sustainable future. They provide several advantages in terms of integration of renewable energy sources, system flexibility, and a cross-sectoral approach that uses synergies between various energy domains. However, this new framework requires smart management tools that can automatically drive an IES to optimal operation, overcoming system complexity and lack of expertise. This paper presented an overview of the available tools for the optimization and management of IES in the perspective of sector coupling. The focus of the analysis was to highlight the spatial dimension and time horizon for which the tools were designed. After a thorough review of the literature, the most relevant papers were selected, and their features were extracted and classified in a broad illustrative table. In addition, particularly representative tools for each spatial scale were further illustrated with their algorithm and case study technical details. It was possible to draw conclusions on the most commonly studied energy sectors and methodologies, as well as to identify gaps and guidelines for future improvement. In particular, the following aspects deserve further studies: i) tackling optimal management over multiple time scales (for considering long-term effects and real-time management simultaneously), ii) combining multiple spatial levels through decomposition methods, iii) including synthetic fuel production also at community level, and iv) promoting the demonstration of the tools in real case studies.

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Abbreviations

CHP	Combined Heat and Power
IES	Integrated Energy Systems
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
PTG	Power-To-Gas
REC	Renewable Energy Community
RES	Renewable Energy Sources
SES	Smart Energy Systems

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