

Review and Assessment of the Different Categories of Demand Response Potentials

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Abstract

Demand Response (DR) is a well-known concept which has been recognized as an increasingly valuable tool to provide flexibility to the power system, to support the integration of Variable Renewable Energy (VRE) resources and to manage the grid more efficiently. In recent years, there have been a growing number of publications focusing on the estimation of different categories of Demand Response (DR) potentials (e.g. theoretical, technical, economic, and achievable) using different methodologies and assumptions in each research study. The contribution of the present study is twofold. Firstly, a literature review is undertaken focusing specifically on the categorization of the scientific approaches used to estimate the different categories of DR potentials. To the best of authors' knowledge, a general procedure for the estimation of each DR potential category is still missing. Therefore, a novel user-friendly and step-by-step theoretical framework for the determination of the different categories of DR potentials is presented. Findings of this study reveal that literature has extensively focused on the estimation of the technical DR potential followed by the economic, theoretical and achievable potentials respectively. A lack of understanding of the different categories of DR potentials was also identified, which sometimes have been unduly used in the literature. The proposed framework is supported on a small sample of numerical approaches and equations which results on a structured approach to bringing consensus to the DR potential assessment.

Keywords: Demand Response (DR), Demand-side Management (DSM), Load Flexibility, Categories of DR Potentials, Renewable Energy.

Nomenclature

$E_{year_com}^k$	Annual Electricity Consumption (commercial)	$P_{max_res}^k$	Maximum Installed Capacity (residential)
$E_{year_ind}^k$	Annual Electricity Consumption (industrial)	n_{FLH}^k	Number of Full Load Hours
$E_{year_res}^k$	Annual Electricity Consumption (residential)	N_{h_year}	Number of Hours in a Year
s_{com}^k	Average Demand Share (commercial)	n_{house}	Number of Households
s_{util}^k	Capacity Utilization Level	FD^k	Percentage of Flexible Demand
E_{com}^k	Commercial Sector Demand	A_{year}^k	Production Capacity
E_{hourly}^k	Hour Electricity Demand	f_{rev}^k	Revision Outages
$E_{hourly(i)}^k$	Hourly Theoretical DR Potential	P_{unit}^k	Specific Capacity of Each Appliance
f_{eq}^k	Market Penetration of Each Appliance	E_{spec}^k	Specific Electricity Consumption
$P_{max_com}^k$	Maximum Installed Capacity (commercial)	E_{unit}^k	Specific Electricity Consumption of Each Appliance
$P_{max_ind}^k$	Maximum Installed Capacity (industrial)	$D_{profile}^k$	Typical Load Profile

1. Introduction

The enhancement of the flexibility in grid operations due to the high penetration of Renewable Energy Sources (RES) in power systems, with great unpredictability and variability characteristic, will be essential in the near future in order to accommodate the intermittent power output, primarily from wind and solar generation systems [1]. There are several possible sources of flexibility for the power system as pointed out by [2] such as wind and solar power generation ratio, flexible generation, network grid expansion, the excess of capacity, curtailment and also the use of Demand-Side Management (DSM) strategies. In order to meet the future electricity demand, public policy-makers should also ensure that supply would be sufficient to satisfy both the energy and the capacity over a forecast planning period [3]. However, only the supply-side resources are used in the Traditional Resource Strategic Planning (TRSP) [4]. On the other hand, for the Integrated Resource Strategic Planning (IRSP) the DSM strategies and other resources are supposed to be considered

34 in the planning model [4]. The integration of large share of variable renewable energy into the energy system requires an
35 integrated energy planning approach since it may increasingly affect the voltage and frequency control of the power
36 systems and therefore the stability and reliability analyses may strongly contribute to addressing these concerns [5].

37 DSM strategies may be considered as *“the practice of shaping the demand patterns and energy use [3]”* in order to
38 address supply shortages, interconnection’s maximum capacity, control the load growth [6], optimize resource allocation
39 [7] or even to mitigate environmental impacts [8] associated with energy production and intensive energy use. According
40 to [8], *“the implementing of managerial measures to produce the resources on the demand-side by influencing the load
41 demand”* can be defined as DSM which can be broadly divided into Energy Efficiency Measures (EEM) and Demand
42 Response (DR) strategies. EEM might be roughly considered as permanent load reductions whereas DR is focused on
43 load flexibility [9]. Consequently, DR strategies can be broadly classified as temporary load reductions (e.g. load shedding
44 or load shifting) [10]. DSM strategies have been developing over time to deal with the economic and environmental
45 challenges brought by the expansion of supply-side energy resources [11]. The main goals of DSM techniques are valley
46 filling, load shifting, peak clipping, strategic load growth and strategic conservation [12]. Load shifting and valley filling
47 strategies clearly can improve the grid load factor and avoid capacity costs, for example [4]. Ref. [11] argue that the
48 integration between these two dissimilar strategies, i.e., the Supply Side Management (SSM) and DSM is essential to
49 achieve a more accurate model for power system planning purposes. Investments in DSM strategies would avoid
50 investments in the supply-side and also in new transmission grids [4]. According to [3], for the most part of power systems,
51 it is more cost-effective to invest in DSM strategies than in the supply-side.

52 Furthermore, the increasing penetration of power generation from intermittent RES [13] (i.e. with limited
53 controllability and predictability [14]), especially from wind and solar power [15], led to the development of intermittency
54 mitigation techniques such as the specific use of DR strategies [16]. DR aims primarily to encourage end-users to reduce
55 electricity usage by certain incentive schemes, especially when electricity prices are high [17]. According to the U.S.
56 Department of Energy, DR can be defined as *“changes in electric usage by end-use customers from their normal
57 consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to
58 induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”*. DR
59 programs can be divided into two main types (i) Incentive-based programs and (ii) Price-based programs [18]. There are
60 also controllable DR programs in which the consumer accepts load curtailment promoted by an external entity under
61 specific conditions [19]. DR programs are getting popular among utilities to match generation and demand in a more
62 effective way [20] and it has a huge potential to improve the reliability of power systems [21]. International Energy
63 Agency (IEA) highlights the fundamental contribution of DR measures for the integration of VRE and also projected that
64 by 2040 nearly 185 GW of flexible demand would be reached in a cost-effective way [22].

65 Traditionally, the balance between supply and demand has been achieved focusing on the supply side, mainly through
66 the building or upgrading of new power plants, transmission and distribution systems [3]. It is worth mentioning that,
67 from the power system’s perspective, a reduction in demand has the same effect as an increase in supply. In this context,
68 as reported by [23], the deployment of DR programs has been seen as an alternative to generation and transmission
69 expansion. Beyond the high capability of reducing the peak load on the power system [24], DR might be used to contribute
70 to power system regulation capacity in order to promote the wind power integration, for example [17]. Peak-demand
71 reductions might result in deferring or avoiding new generation capacities and/or new transmission and distribution
72 systems, in addition to other benefits such as possible reductions in production costs, the need of lower reserve margin
73 capacity, increase of the security of supply [25] as well as lower transmission system utilization [24]. This last aspect is
74 particularly important for power systems in which the transmission congestion problem is even more critical than the
75 generation capacity. For this case, the use of DR strategies would reduce the load requirements primarily during peak
76 times and therefore improving the transmission constraints [26]. DR might also provide some power system services more
77 reliable than conventional generation systems such as spinning reserve [27] and peak load shaving [28]. DR may also help
78 to integrate higher shares of intermittent renewables [29] by shifting and shaping electricity demand in a more cost-
79 effective way compared to traditional options [30]. Therefore, the implementation of DR strategies might reduce
80 customers’ utility bills such as verified in [31], and improve the resource-efficiency of electricity generation in addition
81 to the promotion of social and environmental benefits [24]. Thus, regardless of all the benefits related to the development
82 of smart grids [32], DR is expected to become a valuable energy solution [17], being able to mitigate the variability of
83 RES [33]. The fast DR deployment together with little additional infrastructure is likely to be the most relevant advantages
84 regarding the use of this source of flexibility [34].

85 Consequently, the sustainable and affordable energy transition requires action on the demand-side in addition to the
86 supply-side. However, although DR may offer a set of advantages [18], many barriers [35] still stand for its effective
87 deployment and implementation mostly because of its highly diverse and multifaceted nature. Therefore, it requires
88 research in a wholly holistic context in order to surpass these previously mentioned barriers. For this reason, it is certainly
89 required a diversity of approaches and methodologies to address the different faces of this complex problem which
90 englobes different sectors and applications. A systematic literature review of DSM strategies is addressed by [8] in which
91 the authors proposed a novel theoretical framework in order to unify the methodologies, terminologies and concepts
92 associated with DSM in the literature. Most of the previous reviews have been traditionally focused on specific sectors or
93 power systems and with a particular focus on the qualitative analysis of DR issues, exploring the benefits and challenges
94 of current DR schemes. The number of publications that investigate aspects of the potential of flexible loads has been also
95 steadily growing in the last years [36]. Particularly, there have been a growing number of studies focusing on the

96 estimation of different categories of DR potentials (e.g. theoretical, technical, economic, and achievable) using different
97 assumptions in each research study. However, limited attention has been given to both (1) A review of the different
98 categories of DR potentials and (2) A general methodological procedure to assess each category of DR potential. Despite
99 the large amount of research on the topic and to the best of authors knowledge, a general procedure for the estimation of
100 the different categories of DR potentials is still missing.

101 Based on this context, the following research questions remain partially unanswered by the available literature. 1) *How*
102 *to assess the potential of flexible demand (DR potential) across different sectors?* and 2) *How can each DR potential*
103 *category be distinguished?* Therefore, a more comprehensive analysis is necessary for the topic and the answers to these
104 questions are fundamental to determine not only which are the most relevant factors and parameters to determining each
105 DR category potential but also to evaluate the extent to which these potentials contribute to the transition to a decarbonized
106 energy system. Therefore, this paper aims to be twofold in order to contribute to filling these research gaps. Firstly, a
107 literature review is undertaken focusing specifically on the different categories of DR potentials previously mentioned.
108 Secondly, a user-friendly step-by-step procedure is proposed in order to facilitate the future estimation of DR potentials.

109 The overall structure of this paper is divided into seven main sections and proceeds as follows. This first section
110 contextualizes the research by providing background information on the subject. Section 2 presents the methodological
111 approach of the research and Section 3 provides a theoretical background on DR programs. A review on the categories of
112 DR potentials is further proposed (Section 4). Then the new conceptual framework is presented in Section 5 which
113 represents an outcome of the literature review. Section 6 attempts to discuss the findings which emerged from the literature
114 review. Finally, Section 7 draws together the key findings including its main implications for future research.

115 2. Methodological Approach

116 This work will follow a qualitative data collection technique approach within the research design. The research nature
117 of this study may be termed as an exploratory study [37]. A qualitative study is conducted using the inductive approach
118 in order to generate theoretical concepts. The different categories of DR potentials are assessed based on an in-depth
119 systematic literature review analysis. The systematic literature review conducted in this research has as its main objective
120 to synthesize a body of evidence of the most recent relevant and significant research and to provide a full overview of the
121 current topic in a repeatable, comprehensive and systematic way [38]. Ref. [39] defines a systematic review as “*a*
122 *formalized method for synthesizing a body of evidence in a reliable manner that aims to maximize transparency,*
123 *comprehensiveness and objectivity*”.

124 A four-step process is considered in this research for conducting the systematic review process following the procedure
125 proposed in [37]. Firstly, the formulation of the research questions was established based on the research gap found by
126 the authors. Subsequent to this, a list of potentially relevant research studies using online databases were undertaken in
127 order to generate a list of the most comprehensive research in the field. The key-word searches used as the selection
128 criteria were performed to locate peer-reviewed journals and it was included the following search terms: (a) Theoretical,
129 (b) Technical, (c) Economic, (d) Achievable, (e) Practical, (f) Social (g) Market and (h) Realizable, combined with the
130 terms (i) Demand Response Potential, (j) Demand-side Flexibility, (k) Flexible Demand Potential, (l) Flexible Load
131 Potential, (m) Load Flexibility Potential, (n) Potential of Load Reduction and (o) Load Management. Then, a screening
132 process (by title and abstract) was conducted in the phase of selection and evaluation, excluding the research papers which
133 were not relevant regarding the previously defined research questions [40]. The analysis and synthesis of the results were
134 undertaken breaking down each study in the year of publication, potential DR category, sectoral coverage, spatial
135 resolution and special notes. Finally, a discussion section regarding the main findings was undertaken and a novel
136 comprehensive framework was proposed as a result of this review analysis. Therefore, the methodology was basically
137 divided into the research question(s) formulation, identification, screening process and analysis and synthesis of the results
138 for the included papers as illustrated in Fig. 1. The novel conceptual framework for the estimation of the DR potentials
139 is proposed in a user-friendly manner in order to provide sufficient methodological detail to allow replication.
140

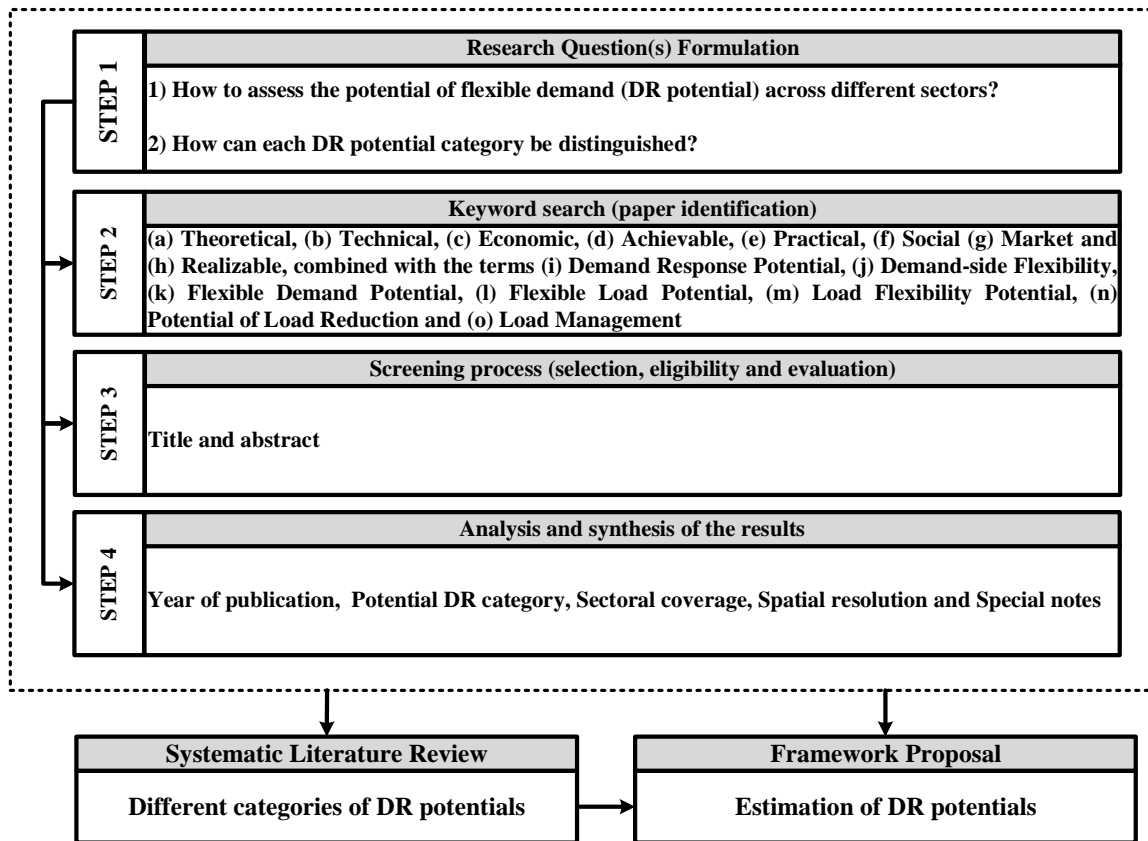


Fig. 1. Methodological approach considered for conducting the systematic review process.

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143 3. Theoretical Background on Demand Response Programs

144 Literature review about DR has been extensively performed along with the last years addressing different aspects of
 145 the field [41]. In [42] the authors selected 117 papers which addressed different DR issues and concluded that “*all major*
 146 *aspects of DR are relatively well covered by model developments (DR pricing schemes, the impact of DR on electricity*
 147 *systems and markets and the participation of selected end-uses in DR schemes)*”. Aspects regarding the different market
 148 mechanisms (i.e. incentive-based or price-based DR mechanisms) have been also addressed by a great number of works
 149 such as in [43] and [44]. Time-sensitive pricing can be classified as non-dispatchable resources [45] and are traditionally
 150 split up into Time-Of-Use (TOU), Critical Peak Pricing (CPP), Real Time Pricing (RTP) and Peak Time Rebate (PTR)
 151 [46]. For dispatchable resources, the decision to dispatch can be broadly divided into reliability (capacity, reserve, energy
 152 or regulation) and economic (demand bidding & buy-back) categories.

153 In [47], the authors categorized the flexibility requirements of VRE systems into technical, economic, and market
 154 potentials with a focus on Europe and particularly addressing the case of the German power system. Studies comparing
 155 specifically the technical with the economic DR potential can be found in [48] for example. The literature review presented
 156 in [47] attempted to address the following topics: flexibility requirements, resource potential in future energy systems and
 157 storage demand. The authors of [49] investigated the DR flexibility potential on office buildings and it has been reported
 158 that the estimation of DR potentials may be further restricted by the variation of thermal comfort performance within the
 159 buildings. A literature review regarding the different methodologies used to assess the potential for flexible use in
 160 buildings energy systems is presented by [50]. Further, the assessment of buildings flexibility potential was addressed by
 161 [51]. To better understand the mechanisms of different DR programs, Ref. [36] classified the different DR programs in
 162 the U.S. electricity markets. Ref. [52] evaluated the economic load management potential with a particular focus on
 163 specific buildings of the industrial and commercial sectors (e.g. offices and schools) for the state of Texas in the U.S. A
 164 methodology to evaluate the load-shifting potential in Small- and medium-sized enterprises (SMEs) is assessed in [53]
 165 based on a case-study of four companies in Germany. The authors of [54] focused on the DR potential (technical and
 166 economic in this case) review analysis of the power-to-heat (PtH) technologies within the European energy system.

167 Fig. 2 presents a brief overview of different DSM programs [55]. DSM options might be valuable according to different
 168 timescales as illustrated in Fig. 2. As stated previously, energy efficiency measures are not dispatchable resources and
 169 energy efficiency can be considered a demand-side resource, which provides permanent demand reductions. Energy
 170 efficiency is usually valued during the energy system planning process and its impacts are mostly related to the long-term
 171 horizon [56]. Price-based programs use time-varying electricity rates (i.e. TOU, CPP and RTP). For this type (i.e. price-
 172 based programs), when the electricity prices are high, customers are intended to reduce their electricity consumption. For
 173 incentive-based programs, however, customers receive money from the utility to reduce their loads at requested times
 174 (e.g. when electricity prices are high or due to reliability problems). Detailed information about Fig. 2 can be found in
 175 [56].

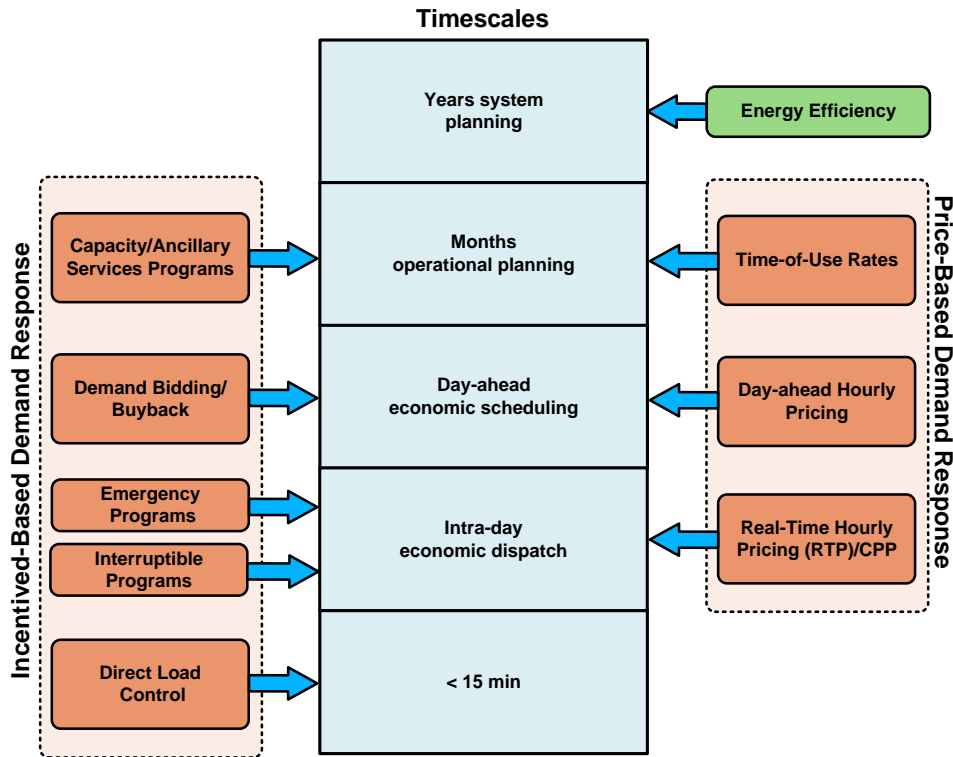


Fig. 2. Role of DSM in Electric System Planning and Operations.
Source: Adapted from [56].

Existing literature usually distinguishes the different categories of DR potentials as Theoretical, Technical, Economic and Achievable. A simplified classification is considered by Ref. [57], which broadly divides the DR potentials into only three categories: technical, economic and achievable. Ref. [58] also consider the same classification of Ref. [57]. In this last case, however, the achievable potential is divided into the Maximum Achievable Potential (MAP) and the Realistic Achievable Potential (RAP). The attitudinal (e.g. consumers' resistance), societal and market barriers which limit the customer participation are taken into account for the MAP definition. The RAP discounts MAP, considering additional constraints related to impediments to DR implementation (e.g. regulatory, political and financial barriers) [58]. Table 1 presents a diverse number of classifications regarding the different categories of DR potentials.

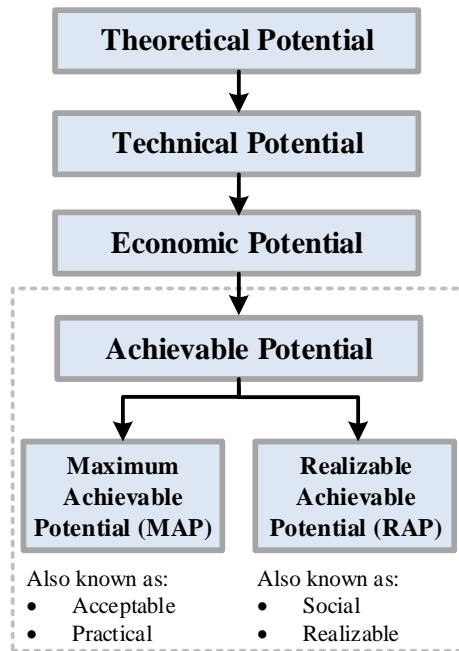
Table 1: Possible DR Classifications Used Along with the Literature.

Reference	Year	DR Categories
[58]	2009	Technical, Economic and Achievable (MAP and RAP)
[57]	2010	Technical, Economic and Achievable
[25]	2010	Technical, Economic and Realizable
[59]	2011	Theoretical, Technical, Economic and Achievable (or Market)
[60]	2015	Theoretical, Technical, Economic, Practical and Social
[61]	2015	Technical and Market (also referred to as Achievable)
[53]	2017	Theoretical, Technical, Economic, Acceptable and Realizable
[62]	2017	Technical, Economic and Achievable
[63]	2018	Theoretical, Technical, Economic and Realizable
[64]	2018	Theoretical, Technical, Economic and Practical

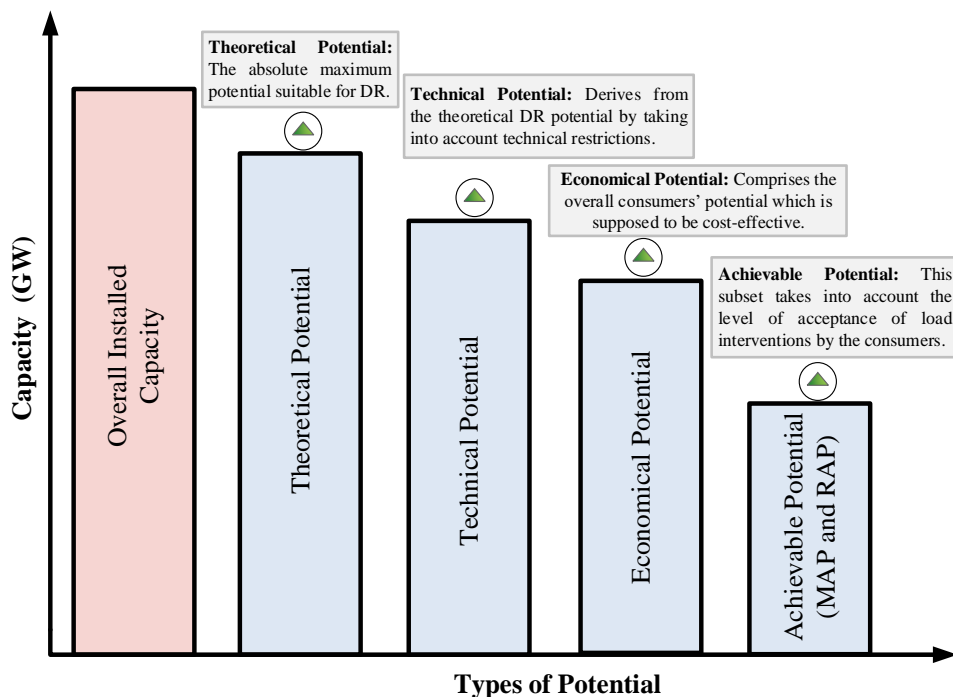
Significant differences can be identified when distinguishing the so-called "achievable" DR potential, which has been treated in different ways within the literature. Some authors split this last concept (i.e. achievable DR potential) into two: MAP and RAP [58], Acceptable and Realizable [53] or even Practical¹ and Social [44]. Other authors do not split the "achievable" DR potential but refer to it with different nomenclatures such as practical [64], realizable [25], feasible [53] or even Market [59] DR potential. Therefore, these terms have been used interchangeably across different research papers within literature. In fact, for all cases, the "Achievable" [59] (or "Practical" [60], "Social" [60], "Realizable" [25], "Feasible" [53] or even "Market" [59]) DR potential would represent a set of one or more barriers to the DR implementation [25] such as summarized in the proposed framework illustrated in Fig. 5 (Section 5). This might suggest the need to standardize this term definition in order to avoid the undue use of these words. Similarly, this would

¹ For the authors of [60], the practical DR potential corresponds to the intersection between the economic and social potential.

200 simultaneously contribute to overcoming the above-mentioned barriers, by making easier future reviewing pathways, for
 201 example.
 202 Therefore, after a systematic literature review, the different classifications regarding the categories of DR potentials
 203 were unified in a standard classification as illustrated in Fig. 3. The different categories of DR potentials *versus* capacity
 204 (GW) together with a brief description of each potential are illustrated in Fig. 4. Along with this paper, for the sake of
 205 clarity, the term that will be most used to describe this last DR potential is “Achievable”.
 206



207
 208 Fig. 3. Overview of the main categories of DR potentials.
 209



210
 211 Fig. 4. Categories of demand response potential *versus* capacity (GW).
 212

213 Source: Adapted from [10,59,60,63].

214 The concept of the ‘Theoretical DR Potential’ is well established in the literature referring to the overall DR potential
 215 available in a power system. This term is supported by Ref. [10] arguing that “*the theoretical potential comprises all*
 216 *facilities and devices of the consumers suitable for DR*”. A similar definition has been further proposed by Ref. [63], who
 217 have argued that the “*theoretical potential generally defines the absolute maximum potential and consists of the entire*
 218 *unrestricted electricity demand*”. However, more recently, literature has emerged (see for example [10], [63] and [65])

219 that offers contradictory definitions for the ‘Technical DR Potential’ concept. Ref. [10], for example, highlights that “*the*
 220 *technical potential includes only those [equipment] that can be controlled by the existing information and communication*
 221 *infrastructure*”. In contrast to [10], Ref. [65] defines that “*the technical potential is the amount of the load that is*
 222 *temporally available for load shifts when taking into account technical peculiarities and legal regulations*”. In agreement
 223 with [65], Ref. [63] argues that “*the technical potential is generally smaller than the theoretical potential, as it takes*
 224 *technical restrictions, such as the number and duration of interventions into account*”.

225 Therefore, while a variety of definitions for the ‘Technical DR Potential’ have been suggested, this paper will use a
 226 similar term definition as suggested by Ref. [63] which is also considered in the evaluation of the technical DR potential²
 227 of [48] and [66]. A general list of definitions derived from the literature review is presented in

228 Table 2 aiming to propose standard definitions for each category of DR potential.
 229
 230

Table 2: Definitions of each DR potential.

DR Potential	Definition	Ref.
Theoretical	The theoretical DR potential comprises the overall (i.e. all facilities and devices) consumers’ potential suitable for DR.	[10,63]
Technical	The technical DR potential derives from the theoretical DR potential by taking into account technical restrictions (e.g., the shifting time, duration and number of interventions).	[63]
Economic	The economic DR potential derives from the technical potential when the costs for implementing DR (e.g. investments and operational) are taken into account. Therefore, it comprises the overall consumers’ potential which is supposed to be cost-effectiveness.	[25,59,63]
Achievable	The achievable DR potential takes into account the level of acceptance of load interventions by the consumers. (1) Maximum Achievable Potential (MAP) : The MAP is restricted by the attitudinal (e.g. consumers’ resistance), societal and market barriers which limit customer participation in DR programs. For this case, it is presumed that no impediments for the effective implementation of DR measures would occur. (2) Realizable Achievable Potential (RAP) : The RAP is derived from the MAP by considering other impediments to DR program implementation (e.g. regulatory, political and financial barriers) which in turn would limit the savings from DR programs.	[58]

231 4. A Review on the Categories of DR Potentials

232 A set of recommendations to incorporate DR into resource planning models is proposed by [24]. Due to a set of barriers
 233 such as legal, policy, economic and societal, the DR implementation is restricted only to selected markets and the
 234 traditional DR programmes mostly focus on large industrial loads [10]. Therefore, literature has mostly focused on the
 235 assessment of DR potential in large-scale and energy-intensive industries [64]. However, a great number of works [67–
 236 69] have been recently addressed the assessment of residential and commercial DR potentials as promising sectors that
 237 would contribute to the power system flexibility [10]. Country-specific analysis of DR potential has been extensively
 238 addressed in literature such as in [63] and [70] for the specific case of Germany and in [71] for Denmark .

239 DR assessments have been traditionally considered using qualitative approach analysis [70]. The evaluation of DR
 240 potential as a quantifiable resource, however, has been assessed only by a few works in the available literature such as in
 241 [70] and the precise quantification of the load flexibility potential is considered a complex task [47]. In [70], for instance,
 242 the authors highlight that the major benefit of employing DR is the reduction of the peak power system capacity, which
 243 represented about 10 GW for the power system evaluated (12% of peak load). For the power system analyzed in [70] the
 244 contribution of DR on the integration of variable renewable electricity power generation is found to be not significant.

245 A great number of studies have estimated the potential of DR resources across different sectors (i.e. industrial,
 246 commercial and residential) at varying scales (e.g. local, regional, national and even across continental regions) [61]. An
 247 up-to-date review analysis is undertaken by [20] which concluded that “*existing DR programs around the world*
 248 *demonstrated a highly asymmetrical development between different regions*”. Ref. [41] highlights the need for the
 249 development of novel DR modeling approaches which would be able to incorporate as many applications as possible and
 250 that consider the interactions of DR with other system resources. Ref. [72] specifically review the DR in the residential
 251 sector including the latest ICT developments. The authors of [28] conducted an extensive literature review regarding DR
 252 programs and also proposed a communication and computation-based DR program for the residential sector. The long-
 253 term impact of DR measures in the industrial, residential and tertiary sectors is assessed in [73] for the Portuguese
 254 electricity system using the OSEMOSYS software tool. The authors of [73] concluded that the implementation of DR
 255 measures would decrease both the overall system capacity (reaching up to 2.2% comparatively to the BAU scenario) and
 256 the total system costs (decreasing up to 2.23%) and would increase the share of renewable energy in the Portuguese power
 257 system. However, Ref. [73] highlight the need to further assess the costs to implement such DR measures since it was not
 258 considered in their assessment. The study of [74] investigated the role of sector coupling in the Brazilian power sector. A
 259 deterministic linear optimization model was considered in this last paper [74] and a simplified model for the DR
 260 representation was used, considering only part of the commercial and industrial sectors as potential flexible loads. The
 261 duration of load interventions is not considered in the modeling approach proposed by [74]. The authors [74] concluded

² The authors of these papers do not mention directly the definition of ‘Technical Potential’ as proposed by [63]. However, we have inferred it because of the assumptions made by those papers to establish their DR potential.

262 that for the specific case of Brazil, the DR contribution is limited to load balancing (reaching up only to 0.04% of the total
 263 annual electricity demand) and this can be mostly explained because of its high renewable potential. On the other hand,
 264 peak load reductions of about 3.3 GW are projected due to the DR implementation for the power system evaluated in [74].
 265 A number of recent studies such as [27] and [41] addressed the key barriers and the challenges to the deployment of
 266 DR. Ref. [41] concluded that DR contributes only to a limited extent in the current electricity market and for this reason,
 267 most of its potential benefits cannot be fully exploited. Ref. [75] considered in their modeling approach that consumers
 268 will have a more active behavior in the future and they will give more importance to quality and sustainability aspects. In
 269 fact, technology advancements on the demand-side have contributed to an increasingly active behavior of consumers [76].
 270 The growing market share of smart appliances brought about by the evolution of smart grids may strongly facilitate the
 271 insertion of demand-side resources such as air conditioning, washing machines and refrigerators without compromising
 272 user comfort. Ref. [75] presented proposals for public, regulatory, and business strategy policies to be implemented by
 273 the Brazilian government in the 2030s. In [17] the authors proposed a coordinated optimization model for the generation
 274 and transmission expansion problem considering the inclusion of DR into the optimization problem. The authors of [77]
 275 presented a method to assess the so-called realizable DR potential for ancillary services purposes.

276 Based on this background, Table 3 gives a general overview regarding the systematic literature review undertaken by
 277 this research paper concerning the different DR potentials addressed along with previous research. The papers were
 278 selected considering those works which (1) explicitly refer to the category of DR potential assessed or (2) the category of
 279 DR potential assessed could be indirectly retrieved. Further, a set of assumptions are reconsidered in order to shape the
 280 addressed DR potentials with the standard definitions proposed by the authors of this review paper.

Table 3: Overview of each potential DR category.

Reference	Year	Potential DR Category	Sectoral Coverage	Spatial Resolution
[78]	2009	Technical/Economic	Commercial	Local Consumer
[58]	2009	Achievable (MAP and RAP)	Industrial, Commercial and Residential	National (U.S.)
[79]	2010	Achievable (RAP)	Industrial, Commercial and Residential	Regional (Midwest ISO region)
[25]	2010	Technical/Economic	Industrial, Commercial and Residential	National (Germany)
[48]	2011	Technical/Economic	Industrial ^a	National (Germany)
[59]	2011	Theoretical, Economic and Achievable	Refrigeration systems ^b	National (Germany)
[80]	2012	Technical and Economic	Industrial, Commercial and Residential	Regional (Eastern Interconnection – U.S.)
[81]	2013	Theoretical	Commercial	Commercial Building
[10]	2014	Theoretical → Technical	Industrial, Commercial and Residential	Continental (Europe and North Africa) ^c
[71]	2014	Technical	Industrial, Commercial and Residential	National (Denmark)
[82]	2014	Technical	Residential	National (Denmark)
[83]	2014	Technical	Residential	Local (Kainuu) ^d
[84]	2015	Theoretical ^e	Industrial, Commercial and Residential	Continental (Europe - 34 countries)
[85]	2015	Theoretical ^f	Residential ^g	National (Belgium)
[86]	2015	Technical and Economic ^h	Residential and Commercial	National (Germany)
[61]	2015	Market → Achievable ⁱ	Industrial, Commercial and Residential	Regional (Shanghai - China)
[70]	2016	Economic /Social → Achievable ^j	Industrial, Commercial and Residential	National (Germany)
[66]	2016	Technical/Economic	Industrial, Commercial and Residential	Continental (West-European)
[87]	2016	Theoretical	Industrial and Residential ^k	Continental (Europe)
[67]	2017	Social → Achievable ^l	Residential and Commercial	National (Germany)
[53]	2017	Technical	Commercial	Company (Germany)
[88]	2018	Theoretical	Industrial, Commercial and Residential	Northern European Countries
[89]	2018	Achievable	Residential	National (Germany)
[68]	2018	Technical	Residential and Service	National (Finland)
[63]	2018	Technical	Industrial, Commercial and Residential	National (Germany)
[90]	2018	Technical	Plug-in electric vehicles	National (Germany)
[52]	2018	Economic	Industry and Commercial	Local (Texas)
[69]	2018	Technical and Economic	Industrial, Commercial and Residential ^m	National (Nigeria)
[73]	2018	Theoretical/Technical ⁿ	Industrial, Commercial and Residential	National (Portugal)
[62]	2018	Technical, Economic and Achievable	Industrial, Commercial and Residential	Regional (Michigan)

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 284 ^a The focus was on energy-intensive industries.

285 ^b The load management potential is evaluated with a particular focus on refrigeration systems considering the potential for each sector that uses this
 286 cross-sectional technology. The base data for the city of Mannheim is used and further extrapolated to the national power system of Germany.

287 ^c The analyses were undertaken for 30 countries (Europe and North Africa). However, for North African countries only energy-intensive industries were
 288 considered due to the scarcity of data. Although the authors mention that the theoretical DR potential is assessed, a set of technical restrictions are also
 289 considered by the authors. Therefore, following the definitions proposed along with this work, the DR potential assessed in [10] should be interpreted
 290 as the 'Technical Potential'.

291 ^d The focus of this work was in the residential sector with metered data collected from 1630 households from Kainuu (Finland).

292 ^e For inference (because the authors do not mention which DR potential is analyzed).

293 ^f The authors also mention that this potential may be underestimated since the results were extrapolated based on a pilot program.

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[§] Here, the flexible potential of five household smart appliances was evaluated based on a set of measurements.

^h The authors mention that “*the results determined a practical shifting potential*”. However, following the definitions used along with this work and the results presented in the paper [86], this definition should be interpreted as the ‘Economic Potential’.

ⁱ Following the definitions used along with this work, the “Market” DR potential cited in the paper would correspond to the “Achievable” DR potential.

^j The author mention that “*a model-based assessment of the economic DR potential in Germany is presented*”. Further, the author refers to the estimation of an “*approximated social potential*”.

^k The following sectors were considered by the authors: industrial, cooling, households, heat pumps and e-mobility.

^l Following the definitions used along with this work and the results presented in the paper [67] this definition should be interpreted as the achievable potential.

^m The DSM potential is assessed considering different levels of industrialization.

ⁿ The authors mention that “*the theoretical potential of DR is computed*”. However, they also consider a set of technical restrictions in the model formulation. Therefore, following the definitions used along with this work, the definition that would be considered here is precisely the ‘Technical Potential’.

The following subsections will particularly focus on a review analysis regarding the different DR potentials illustrated in Fig. 3.

4.1 Theoretical DR Potential

Ref. [59] addressed the potential for load management in Germany with a particular focus on the refrigeration systems across different sectors (i.e. industrial, commercial and residential). The authors of [59] addressed the theoretical (4.2 GW), economic (3.2 GW) and achievable (2.8 GW) DR potential. The achievable potential corresponds to 66% of the theoretical potential for the power system evaluated in [59].

Ref. [88] estimated the theoretical DR potential across different sectors for seven Northern European countries (Denmark, Norway, Sweden, Finland, Lithuania, Estonia and Latvia) as 12-23 GW considering a peak load of about 77 GW.

The total theoretical DR potential for Europe (34 countries) was assessed by [84], estimating a total of 800 TWh for suitable DR processes across industrial, commercial and residential sectors. This represents a value slightly higher than 52 GW (9.4% of peak load) split into residential (42%), industrial (31%) and commercial (27%) sectors. The authors of [84] concluded that the share of flexible loads for the industrial sector is higher for countries with higher shares of industrial electricity consumption such as Sweden and Norway, for example [84].

4.2 Technical DR Potential

The technical DR potential is addressed in [86] for the German power system (specifically for the residential and commercial sectors) which reach up to 8 GW by 2030. Ref. [86] also conducted an economic analysis for the residential sector and concluded that the income generated by load management is not enough to cover the investment in Information and Communications Technology (ICT) and therefore the DR was proved not to be cost effective.

The technical DR potential of flexible demand for the Danish power system is assessed in [71] across industrial, commercial and residential sectors using two approaches. Firstly, a bottom-up approach is considered to assess the flexible load potential for each sector (i.e. industrial, commercial and residential) for a 100% RES in 2050. Then, the EnergyPLAN software is applied to perform the simulations in order to identify the most adequate levels of the flexible loads for the power system assessed. It is worth mentioning that the software EnergyPLAN has been extensively used to the simulation of future energy scenarios focusing on the large-scale integration of RES into the power system [91] and recently it has been also used to the inclusion of DR into the long-term simulations as addressed by [71].

4.3 Economic DR Potential

The economic DR Potential (also referred to as Techno-Economic DR Potential [59]) derives from the technical DR potential. In this case, however, the costs to activate this technical potential should be taken into account. According to [59], “*the economic potential describes the cost-effective application of load management*”. The overall costs comprise both the investments and operational costs [25]. Traditionally, the DR potential that is considered cost-effective would technically suggest that the overall costs of implementing such DR measures are lower than the cost of energy supply. The incremental cost of electricity from peaking generators and the use of both cost and risk combination of portfolios with and without DR (i.e. portfolio analysis of DR) are other examples of how literature has been evaluated the cost-effectiveness of DR strategies [62].

The potential of technical and economic DR potential for wind integration is assessed by [25]. The authors of [66] identified the least-cost options for West-European countries for the year 2050 through the assessment of five options which included flexibility potential of DR strategies. This last paper assessed the economic DR potential and considered the costs for load shifting ranging from 2 to 100 €/kW and the costs for load shedding varying between 200 and 5000 €/MWh, depending on the process assessed. For the power system evaluated in [66], the total system costs can be reduced up to 3% by the implementation of the DR measures. Ref. [41] point out that currently one of the most fundamental questions regards about how DR should be priced in terms of investment and operational costs. These cost aspects remain still unclear and should receive attention in future works.

352 4.4 Achievable DR Potential

353 This subset takes into account the level of acceptance of load interventions by the consumers. Few published studies
354 have attempted to evaluate the achievable DR potential. Most of the studies which attempted to assess the achievable DR
355 potential have been limited to convenience samples and in general, it has been restricted to the analysis of small regions
356 such as in [61] and [62]. In [59], for example, the achievable potential was estimated specifically for the refrigeration
357 sector in Germany. However, few published studies have attempted to systematically evaluate the achievable DR potential
358 of large interconnected electric power systems.

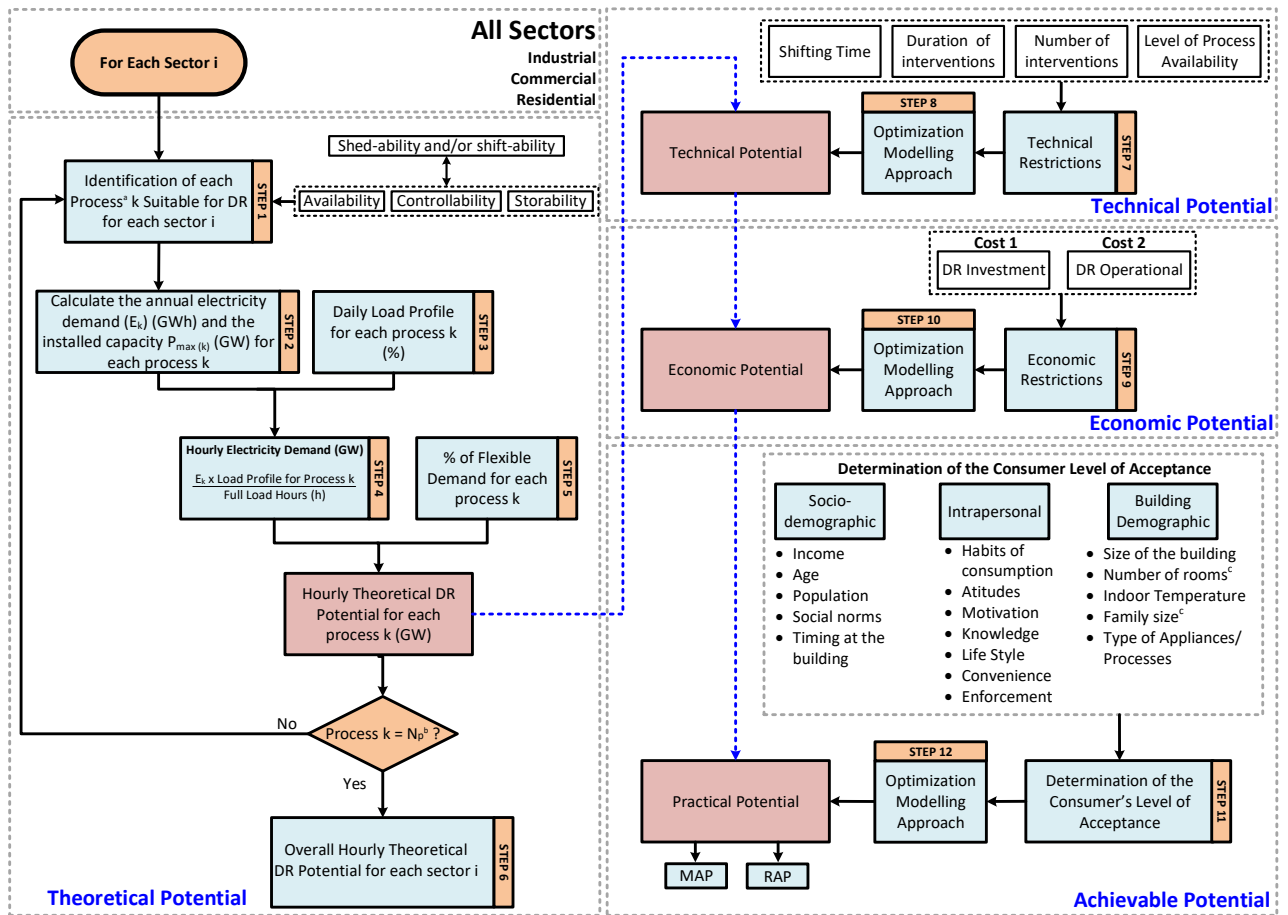
359 In [67] the shifting load potential is assessed for the German power system constrained by the consumers' acceptance
360 and also limiting the disconnection rates (which in practice means that the applications must be reconnected after a
361 predefined time). Therefore, the authors of [67] considered the social acceptance of DR (specifically for the residential
362 and commercial sectors). Ref. [41] highlights that *"human nature is a further issue which compounds the problem of
363 market design for demand response. While large generators typically exhibit economically rational behaviour through
364 their profit maximising objective, smaller customers do not show the same rationality in their consumption decisions"*.

365 The authors of [92] highlight that the effective implementation of DSM strategies (e.g. DR measures) strongly depends
366 on social acceptance. Ref. [70] considered the calculation of an *"approximated social potential"*. Due to the set of
367 complex features associated to the estimation of the achievable DR potential, it is probable that the author of [70] used
368 the term 'approximated' in his definition because of the highly diverse, multifaceted and complex nature of the achievable
369 DR assessment.

370 5. A New Conceptual Framework to estimate DR potentials

371 There are two main methods for assessing the flexible load potential namely aggregated and decomposition methods
372 [71]. For the aggregated approach, market mechanisms are used to assess changes in demand in accordance with market
373 conditions (e.g. electricity price change) [71]. For the methodology proposed in this paper, the potential of flexible loads
374 is assessed by broadly splitting up the potential candidates into a flexible and an inflexible component for each category
375 (i.e. using the decomposition method) such as proposed by [63]. Then, for each sector, the decomposition of electricity
376 consumption into several process/appliances is realized and individually assessed such as suggested and applied by several
377 works in the literature [71]. Load flexibility may be also assessed in terms of the amount of electricity (GWh), power
378 (GW), time, type (e.g. load shedding and load shifting) as well as cost [92]. Depending on the variables used in the
379 analysis, different DR potentials may be assessed (see Fig. 5).

380 Ref. [10] points out that because of the different categories of DR potentials and considering the diverse set of
381 constraints evolved, the DR potentials need to be treated separately. Therefore, after conducting a systematic literature
382 review, the need for a framework which would systematically support the estimation of each DR potential was identified
383 as the research gap. In addition, different methodological approaches have been considered and literature mostly focuses
384 on the estimation of country-specific potentials and in a very limited extent research in the topic has considered the step-
385 by-step procedure to assess each category of DR potential. Consequently, based on the prior knowledge obtained by the
386 conducted systematic review analysis an improved conceptual framework is proposed. The general overview of the
387 methodological approach for assessing the different categories of DR potential is illustrated in Fig. 5.
388



^aFor the sake of simplicity, along with the flowchart, it will be used the term "process", which would refer to both "process" or "appliance".

^b N_p represents the number of the processes.

^cSpecifically for the residential sector.

Fig. 5. Key steps of the proposed framework for the estimation of each DR potential category.

The following subsections will present the proposed twelve-step methodology to identify the different categories of DR potentials illustrated in Fig. 5. The methodology is divided into the four main categories for DR potentials (i.e. Theoretical, Technical, Economic and Achievable). The theoretical DR potential is addressed in the subsection 5.1 following the first six steps (step 1 to step 6). The technical DR potential derives from the theoretical DR potential by applying step 7 and step 8 as described in subsection 5.2. Departing from the technical DR potential, the economic DR potential is discussed in subsection 5.3. This estimation requires an assessment of the costs of implementing DR as presented in step 9 and step 10. Finally, subsection 5.4 addresses the achievable DR potential through the last two steps (step 11 and step 12) for which the consumers level of acceptance is considered.

5.1 Theoretical DR Potential: Step 1 to Step 6

This section aims to present the step-by-step procedure for the estimation of the theoretical DR potential.

Step 1: Identification for each process/appliance suitable for DR for each sector

The starting point of the analysis comprises the identification of the potential flexible loads (processes and/or appliances) suitable for load shedding and/or load shifting for each sector³ desired (Step 1). This identification has been traditionally undertaken through a qualitative assessment of technologies [53]. It is worth mentioning that this identification would require different criteria evaluation for each sector (i.e. residential, commercial and industrial). The shed-ability and/or shift-ability characteristics of each process/appliance would be taken into account which is also interconnected with the following technologies characteristics: availability, storability and controllability [49].

Table 4 presents the main processes/appliances with some degree of DR potential, but are not limited to only these applications and would vary between countries and sectors. To give a well-known example for the sake of clarity, for the residential and commercial sector, the controllability *versus* non-controllability and storability *versus* non-storability of the service might be taken into account for the selection of the suitable processes/appliances for DR. Therefore, the

³ It is worth mentioning that according to [10], traditionally "for processes with very high utilization rates - as they are found in energy-intensive industries - only load shedding without previous or subsequent balancing can be implemented. In residential and commercial sector, typically both load shifting and shedding can be realized".

414 suggested criteria used along with this work to select the suitable processes/ appliances for DR is whether it is storable
 415 and automatically controlled. This can be seen in the case of the refrigerator (for the residential sector) which has a
 416 storability characteristic and therefore could be considered suitable to contribute to DR. Similarly, the washing equipment
 417 (e.g. washing machine, dishwasher and tumble dryers) would be suitable because of its controllability characteristic. The
 418 independence between processes might be added to the selection of suitable DR processes for the industrial sector although
 419 this is not considered a trivial task [71]. For this reason, most of the previous studies do not take into account this last
 420 aspect in the selection process.

421
 422 Table 4: Representation of the main processes with some degree of DR potential [60,84].

Residential	Industrial	Commercial
Air-conditioning	Paper machines	Air-conditioning
Washing machines	Non-metallic minerals	Ventilation
Tumble Dryers	Non-ferrous metals	Refrigeration
Dishwashers	Chemical and petrochemical	Storage water heater
Water heaters	Iron & steel	Storage heater
Refrigerators and freezers	Wood products	Wastewater treatment
Heating systems and electric boilers	Air Separation	Pumps in the water supply
	Cement Mills	Cold storages
	Wastepaper processing	

423
 424 **Step 2: Quantification of Flexible Loads: Calculation of the Annual Electricity Demand and the Maximum**
 425 **Installed Capacity**

426 The estimation of the annual electricity demand and the maximum installed capacity for each process/appliance k over
 427 each sector i should be calculated in this step. However, this calculation strongly varies among sectors. This aspect can
 428 be mostly explained by both the technical differences across each process/appliance and also considering the scarcity and
 429 sparsity of available data. For this reason, for the industrial and commercial sectors, a top-down approach is traditionally
 430 considered in the literature whereas a bottom-up approach is usually considered for the estimation of the annual electricity
 431 demand for the residential sector. Therefore, these assumptions are taken into account in this step. A summary of the
 432 equations used to the quantification of the flexible load potential for each sector is mostly driven based on the assumptions⁴
 433 of [60] and is provided in Table 5.

434 The quantification of the DR potential for energy-intensive industries is based on the specific electricity consumption
 435 and production capacities. As for the commercial sector, due to data scarcity, the combination between each individual
 436 process and its share is frequently used to categorize the overall electricity consumption. Therefore, the calculation of the
 437 annual electricity consumption is based on the average annual consumption.

438 For the residential sector, the specific electricity consumption might be calculated considering the technical
 439 characteristics of each appliance and therefore it would vary across different appliances and regions. Detailed calculation
 440 of the specific electricity consumption of each appliance can be found on [60]. To give a well-known example for the sake
 441 of clarity, the duration and frequency of use for washing equipment could also be taken into consideration for estimating
 442 its annual electricity consumption. Average values can also be used based on equipment data sheets. It is worth mentioning
 443 that the overall potential of the flexible demands mainly for the residential sector is highly dependent on the appliances
 444 characteristics (i.e. type, power, efficiency and rate of each equipment) and also on the pattern of consumption of these
 445 appliances which are affected mostly by the per capita income and the willingness to use more efficient technologies [93].

446
 447 Table 5: Summary of the equations used to the quantification of the flexible load potential for each sector.

Sector	Equation	Definition
Industrial	$E_{year_ind}^k = A_{year}^k \cdot E_{spec}^k \cdot S_{util}^k$ (1)	Annual electricity consumption (GWh)
	$P_{max_ind}^k = \frac{E_{year_ind}^k}{N_{h_year} \cdot (1 - f_{rev}^k) \cdot S_{util}^k}$ (2)	Maximum Installed capacity (GW)
Commercial	$E_{year_com}^k = E_{com}^k \cdot S_{com}^k$ (3)	Annual electricity consumption (GWh)
	$P_{max_com}^k = \frac{E_{year_com}^k}{n_{FLH}^k}$ (4)	Maximum Installed capacity (GW)
Residential	$E_{year_res}^k = n_{house} \cdot f_{eq}^k \cdot E_{unit}^k$ (5)	Annual electricity consumption (GWh)
	$P_{max_res}^k = n_{house} \cdot f_{eq}^k \cdot P_{unit}^k$ (6)	Maximum Installed capacity (GW)

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⁴ The author of [60] also includes equations for estimating the overall potential of load reduction and load increase for each hour. We highlight that these equations could also be included in the framework proposed in this paper. In this case, the calculation of the potential of load reduction and increase should be performed after Step 2 using the set of equations presented in [60].

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Step 3: Daily Load Profile for each process

In order to calculate the Hourly Electricity Demand in the next step (i.e. Step 4), and therefore, to account for the temporal availability of DR potential, the typical load profiles for each process/appliance should be estimated by using metered data or considering the typical profile patterns according to the available literature [60]. The selection of the representative load curves on a daily, weekly and/or seasonal base is of particular importance and it would be considered if there is available data [60]. Traditionally, energy-intensive industries run at full capacity over the entire year, due to both the huge heterogeneity of processes and because of its high utilization rates. Therefore, a constant load profile over the entire year is usually considered in the literature such as in [10] and [63].

The load profile is dependent on a set of diverse variables and therefore it can be considered dynamic, non-linear and time-varying [41]. For this reason, the future⁵ projections are considered by literature highly uncertain. Detailed end-use load profiles for each customer segment considering both a reasonable sample and length of time would also potentialize the future estimations of DR potentials. Traditionally, the load profiles for all DR processes/appliances remain unchanged for the estimation of the flexibility potential in future years such as considered in such as in [10] and [63].

Step 4: Hourly Electricity Demand

At this step, the hour electricity demand should be calculated. Combining the annual electricity demand (Step 2) with the load usage pattern (Step 3) and also taking into account the full load hours, the hourly electricity demand (Step 4) can be calculated for each process k according to Eq. (7) [63].

$$E_{hourly}^k = \frac{E_{year}^k \cdot D_{profile}^k}{n_{FLH}^k} \quad (GW) \quad (7)$$

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Step 5: Percentage of Flexible Demand for Each Process/Appliance

For each process/appliance k, the percentage of flexible demand needs to be estimated to further calculate the Hourly Theoretical DR Potential for each process/appliance k. The share of flexible demand for each process/appliance would strongly differ between each other.

Step 6: Overall Hourly Theoretical DR Potential for Each Sector

For each sector i and year y, the sum for all processes k which contribute to the DR potential gives the overall hourly theoretical DR potential which can be calculated by using Eq. (8). Therefore, the sum of all suitable DR processes/appliances comprises the total DR potential of a power system [63].

$$E_{hourly(i)}^k = \sum_{k=1}^N (E_{hourly}^k \cdot FD^k) \quad \forall k, y \quad (GWh) \quad (8)$$

483 5.2 Technical DR Potential: Step 7 to Step 8

484 The following steps (Step 7 and 8) allows the estimation of the technical DR potential.

485

486 Step 7: Technical Restrictions

487 This step comprises the inclusion of a set of technical restrictions in order to estimate the Technical DR Potential. The shifting time, duration and number of DR interventions can be considered the most important technical restrictions to be taken into account in addition to the level of availability of each process/appliance.

489

490 Step 8: Optimization Modelling Approach

491 The use of an optimization modeling approach is usually⁶ considered to support the assessment of the technical DR potential of the overall electricity system. Within the optimization model, the technical restrictions (Step 7) would constrain the planning model. Different optimization modeling approaches (e.g. linear programming or stochastic programming) can be used, but the detailed description of each optimization approach is out of the scope of this research paper.

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⁵ The extrapolation of the flexibility potential for each process/appliance is necessary when the potential of flexible loads is quantified for future years (y). This stage would require a broad literature review and in general it is based on available statistics of recent technology developments. To give a well-known example for the sake of clarity, for the residential sector, the increasing intensity of use of appliances should be used in the extrapolation of data [60]. Different shares of flexible demand would also be taken into account when extrapolation for future years is considered since it could change over years. This happens because of two main reasons: the electricity consumption would increase and the future DR potential would also change according to the deployment of the technologies [63].

⁶ The use of simulation models is still possible such as considered by [71].

497 **5.3 Economic DR Potential: Step 9 to Step 10**

498 The economic DR potential can be further assessed by the use of Steps 9 and Step 10.

499
500 **Step 9: Economic Restrictions**

501 The economic restrictions need to be taken into account in order to assess the economic DR potential. Here, two
502 different costs are traditionally associated with the DR. The investment costs (i.e. associated with the ICT necessary to
503 automatized adjustment control, smart metering systems and program design) and the operational costs (i.e. variable and
504 annual fixed costs) [48]. The operational costs might also include marketing and other administrative maintenance costs
505 [94].

506
507 **Step 10: Optimization Modelling Approach**

508 See Step 8. For this case, the economic restrictions (Step 9) would be also used to constrain the optimization model,
509 which would support the final assessment of the economic DR potential of the electricity system.

510 **5.4 Achievable DR Potential: Step 11 to Step 12**

511 Finally, the following steps (Step 11 and Step 12) support the estimation of the achievable DR potential.

512
513 **Step 11: Determination of the Consumers' Level of Acceptance**

514 The estimation of the achievable DR potential comprises a difficult task since it depends on the evaluation of a set of
515 qualitative variables (e.g. informational, legal, technical, organization and financial barriers in addition to the lack of
516 consumers' experience [59]) such as illustrated in Fig. 5. The authors of [47] agree with this and also point out that "*the*
517 *determination of the market potential for a certain technology imposes challenges in setting a valid scientific*
518 *methodology*". The main barriers include the lack of consumers' acceptance, lack of enforcement, market structure and
519 information gaps [25]. The end-user behavior plays a major role in the effective implementation of DR measures [28].
520 Ref. [67] point out that the maximum shift duration, for example, for each process/appliance mostly depends on the
521 customers' acceptance. Results from earlier studies such as [95] and [96] demonstrate that consumers' responses to prices
522 might be asymmetric, increasing considerably their consumption on off-peak periods but with limited reductions on the
523 electricity consumption during on-peak times. Ref. [85] assessed the flexibility potential of five household appliances
524 based on real measured data for a large pilot test in Belgium and reported that the flexibility potential of household smart
525 appliances is highly asymmetric. Therefore, the willingness to accept load interventions (i.e. load shedding and/or load
526 shifting) by end-users may be evaluated using both qualitative and quantitative analysis [49]. The effective DR
527 implementation (i.e. achievable DR potential), is thus lower than the economic DR potential since it depends on the level
528 of consumers' acceptance.

529
530 **Step 12: Optimization Modelling Approach**

531 See Step 8. For this case, the restrictions from Step 11 would be also considered to constrain the optimization model,
532 in order to properly account for the flexibility potential of the consumers and reach a final assessment of the achievable
533 DR potential of the electricity system.

534 **6. Discussion of the Findings**

535 This section will attempt to discuss the main findings which emerged from the literature review. This study found that
536 different methodologies have been used to the evaluation of the different categories of DR potentials. Ref. [97] reviewed
537 the DR experience in Europe and highlighted that "*studies on the economic and technical potential of DR vary significantly*
538 *in methods, sample sizes and results*". In [63] an overview with a focus on DR potentials is addressed. The authors of
539 [64] point out that in the review analysis of DR potentials undertaken by [63] "*the authors remark significant variations*
540 *in the considered studies, which may be explained by a different scoping and assessment method of the analyzed demand*
541 *response potential*". Therefore, previous studies vary strongly in their findings concerning DR potentials.

542 According to [72] the "*lack of experience with demand response has necessitated the employment of numerous*
543 *assumptions in the modeling approaches adopted. As a consequence, it can be argued that the estimations of the benefit*
544 *of demand response are dependent on these assumptions and an accurate evaluation has yet to be achieved*". For this
545 reason, the DR potential estimation varies between studies even considering the same power system such as better
546 demonstrated by [63]. In this context, Ref. [41] also points out that because of both the lack of experience and
547 understanding of the complex nature of DR, superficial results have been obtained by great part of works published in the
548 literature due to its simplistic models and consequently several analyses might be oversimplified with unrealistic results
549 and which do not represent correctly the reality. Ref. [98] points out that these differences occur mostly because of the
550 different methods used for the estimation of DR potentials. To give a well-known example for the sake of clarity, some
551 authors estimate the average potential whereas others use an hourly estimation of DR potential.

552 Ref. [63] analyzed six different projections which estimated the DR potential for Germany and pointed out that the
553 most of previously published works consider "*only the maximum potential and do not consider temporal availability in*
554 *detail*". However, the DR potential is strongly dependent on temporal availability (e.g. hour of the day), indoor
555 temperature and season, for instance [63]. The technical DR potential for Germany was recently addressed by the authors

556 of [63]. The maximum technical DR potential considering both load shedding and load shifting estimated by [63] was
557 nearly 25 GW (using data for the year 2013). However, the authors of [63] point out that this potential will never be
558 available because the electricity consumption varies for each hour (i.e. daily, weekly and season for instance). Therefore,
559 the temporal availability [99] and the spatial distribution [10] of the flexible loads are of particular importance. The
560 temporal availability has been traditionally taken into account through the identification of typical daily load profiles. Due
561 to the lack of measurements, typical demand load patterns are traditionally considered based on data from the available
562 literature. Flexible loads for commercial and industrial sectors have been traditionally estimated based on their annual
563 electricity consumption. Ref. [63] also addressed the question if the technical DR potential is available when needed (i.e.
564 mostly during on-peak times) and concluded that the maximum DR potential for the power system evaluated occurs during
565 off-peak times (i.e. only a small share of the DR potential is available when the power system mostly needs). The
566 maximum hourly potential provides a flexible demand slightly lower than 14 GW (which is considerably lower than the
567 maximum available capacity of about 25 GW) for the power system evaluated in [63].

568 Based on the literature review it became obvious that the classification of the different categories of demand response
569 potentials are far from being consensual and the methods for their estimation are not yet fully established. The framework
570 presented in Fig. 5 allowed to provide guidelines for bringing consensus to the DR potential classification and solving the
571 estimation problem, supported on a solid scientific background derived from the literature review. Given the complex
572 nature of the estimation problem and the heterogeneity of the sector and power systems, just a small sample of numerical
573 approaches and equations are proposed but the user-friendly and step-by-step nature of the theoretical framework is
574 deemed to be of high benefit for the power systems community and decision makers.

575 7. Conclusion & Outlook

576 This paper addressed two central issues and the findings make several contributions to the current literature. The
577 strengths of this study include the in-depth systematic review analysis regarding the different categories of DR potentials,
578 which allowed not only to reach some consensus on the definition of DR categories but also on the main steps to be
579 followed for its estimation.

580 Firstly, it was demonstrated - through an in-depth systematic review analysis - that there is a lack of understanding of
581 the different categories of DR potentials, which sometimes have been unduly used by the available literature. The DR
582 potentials were standardized into four main categories: Theoretical, Technical, Economic and Achievable. Findings of
583 this study also reveal that there is a general agreement in the literature regarding the definition of the theoretical and
584 economic DR potentials. However, significant differences can be identified when distinguishing the so-called technical
585 and achievable DR potentials, which has been defined in different ways within the literature. Therefore, the unification of
586 these different classifications was proposed in order to avoid misleading research on this topic. This would simultaneously
587 contribute to overcoming the above-mentioned barriers, by making easier future reviewing pathways, for example. The
588 research presented here also confirmed that different terms have been used to refer to "DR potentials", which includes
589 mostly: (1) Demand Response Potential, (2) Demand-side Flexibility, (3) Flexible Demand Potential, (4) Flexible Load
590 Potential and (5) Load Flexibility Potential, which oftentimes has been used interchangeably in the literature.

591 Secondly, a well-founded and user-friendly framework - which would strongly help the quantification of the DR
592 flexibility across different sectors and applications - is proposed. In contrast to other review papers which addressed
593 different DR issues, the scientific contribution of this research relies mostly on the novel theoretical framework based on
594 an integrated approach for the determination of the different categories of DR potentials.

595 The DR potential estimation may somewhat vary between studies for the same power system and this can be mostly
596 explained by the fact that some works consider the theoretical potential, which represents an upper bound for the other
597 potentials (i.e. technical, economic and achievable). Overall, the studies reviewed here clearly indicate the importance of
598 the temporal availability of DR applications which has been neglected by part of the published works. The findings also
599 raised important theoretical issues that have a bearing on the quantification of the DR potential in the long-term. The
600 estimation of the future DR potentials is particularly valuable in order to contribute to a sustainable future. The evidence
601 reviewed here seems to suggest a pertinent role for the use of effective approaches for the detailed estimation of end-use
602 load profiles for each customer segment considering both a reasonable sample and length of time which would potentialize
603 the future estimations of all categories of DR potentials. Also, the determination of the technical suitability and the load
604 flexibility potential for each end-use-level and customer segment is considered to be essential to accurately reflect in
605 realistic DR potentials future estimations.

606 To summarize, the holistic assessment of the potential contribution of DR needs to surpass a set of barriers including
607 technical and non-technical ones. Regulatory barriers can be considered one of the most important aspects to be addressed
608 in order to improve the deployment of DR and also to enable customer participation in DR initiatives. The non-technical
609 barriers for the adoption of DR mechanisms would also be taken into account in order to assess the achievable DR
610 potential, for example. Finally, it can be concluded that although many advances have been observed over the past years,
611 primarily in developing countries, many challenges and barriers (e.g. technical, market and behavioral) associated with
612 the DR deployment still exists and appears as potential challenges for the deployment and dissemination of DR strategies.
613 The effectiveness of DR programs is also strongly dependent on government policies and regulations that should have
614 reliable and long-term support. Therefore, the outcomes of our literature review also lead to the conclusion that the
615 evaluation of potential benefits of DR measures should be addressed in a holistic manner, considering the external benefits
616 for the entire energy system (e.g. using a portfolio analysis) which would potentialize the cost-effectiveness of DR and
617 become a more attractive demand-side option.

618 A few limitations need to be noted regarding the present study. Firstly, it is worth mentioning that the generalizability
619 of much published research on this issue is problematic and it is not considered a trivial task since each power system has
620 its particular characteristics. Secondly, more research on this topic needs to be undertaken, addressing the trade-offs of
621 each methodology that had been considered to evaluate the different categories of DR potentials. However, despite these
622 limitations, we highlight the potential of replicability of the methodology proposed in this paper to evaluate the different
623 categories of DR potentials across both different customer segments and power systems.

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