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Review

Gameful Green: A Systematic Review on the Use of Serious Computer Games and Gamified Mobile Apps to Foster Pro-Environmental Information, Attitudes and Behaviors

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Abstract: As the issues related to climate change intensify, new methods to raise awareness of environmental issues, foster pro-environmental attitudes and behaviors, and offer a viable alternative to traditional environmental education are needed. In recent years, various computer games and mobile apps targeting sustainability-related information, attitude, and behaviors have been developed. In this systematic review, we aimed to verify which pro-environmental information, attitudes, and behaviors are targeted by serious games and gamified apps, how their efficiency is tested, and the main results. A total of 29 studies were included in the analysis. The results show that serious games and apps were used to decrease energy consumption, water spending, and food consumption, and increase sustainable mobility. Furthermore, technology was used to offer pro-environmental education regarding a myriad of issues. Most interventions were successful and some of them did have significant effects while others provided only short-term changes. The limitations of the current approaches are discussed together with some future expansions that can help develop more efficiency in this domain.

Keywords: serious games; gamified mobile apps; sustainable behaviors; pro-environmental education; climate change

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1. Introduction

The severe deterioration of the natural environment and climate change pose an existential threat to all life on the planet. Although it is caused by human activities, changing environmentally harmful behaviors has proven to be an extremely difficult task. Over the last few years, novel methods aiming to provide meaningful pro-environmental information and promote consistent attitudes and behaviors were tested. Among them, various pieces of technology, such as serious computer games and mobile apps are an opportunity to multiply and strengthen nature conservation behaviors [1].

Interactive technology has the potential to educate and engage individuals, especially the young ones, on issues related to climate change and sustainability and to facilitate the development of useful thoughts, feelings, and actions [2]. Especially in today's environment, there is an urgent need to create new ways to engage different segments of the population in the issues related to nature protection and global climate change, to increase the efficiency of environmental education, and to involve young people in pro-environmental behaviors.

Games aimed at environmental education are considered "serious games", designed to go beyond simple entertainment and offer multiple learning opportunities. Through rules, goals, rewards, and the way they encourage divergent thinking, they promote learning and are considered appropriate for the adolescent and young adult populations [3,4]. Similarly, apps designed for formal and informal environmental education promote awareness of climate change as well as change in pro-environmental attitudes and behaviors. A large part of these specific apps includes gamified features and aims to keep and increase users' engagement in the long term [5]. Regardless of the device used to install and play them,

serious games and apps that steer environmental education are purposeful applications or pieces of software that share gamified components or features. With a long history of development and usage, serious games are more numerous than apps and consequently more often reported in interventions.

Thus, it becomes easy to see the significant recent increase in simulations, serious games, and apps developed for use in environmental education. However, these games and apps have a wide variety of purposes beyond delivering a simple pro-environmental message [6]. As such, it is important to investigate the outcomes that the game and app developers aim to engage, how they intend to achieve this, and the level of success in implementing their goals. The review aims to verify which pro-environmental information, attitudes, and behaviors are targeted by serious games and apps, how their efficiency is tested, and the main results of such research endeavors.

1.1. Environmental Education: Pro-Environmental Information or Knowledge, Attitudes, and Behaviors

Environmental education is "aimed at producing a citizenry that is knowledgeable concerning the biophysical environment and its associated problems, aware of how to help solve these problems, and motivated to work towards their solution" (p. 31) [7]. In other words, the overall aim of environmental education is to influence individuals to relate appropriately to environmental issues in accordance with the goals of the society to which they belong. Of course, the ultimate target is to generate pro-environmental behavior, thus persuading people to act independently in favor of nature, guided by their own will in each specific situation.

Generally, pro-environmental behavior is very difficult to initiate and influence [8]. Therefore, many intervention programs based on pro-environmental education methods initially aim to provide information and enrich participants' environmental knowledge, counting on the fact that this knowledge will gradually form the basis of pro-environmental attitudes and values. Environmental attitudes include any attitude towards the natural or built environment but, usually, the researchers who study them focus on the care and concern of the individuals towards nature and on the degree to which the individuals care about the state of the natural environment. Therefore, the environmental attitude corresponds to the individual's preoccupation with the environment as something that deserves to be understood, protected, and strengthened. A fortunate subsequent process would be for the attitudes to determine behaviors in favor of preserving the natural environment. Pro-environmental behavior can be defined as "the behavior which is generally (or according to knowledge of environmental science) judged in the context of the considered society as a protective way of environmental behavior or a tribute to the healthy environment" [9] (p. 252).

Following this line of reasoning, behavioral change cannot occur without beneficial information and pro-environmental attitudes, so those who practice environmental education must provide environmental knowledge to their participants, and then foster corresponding values and attitudes. However, Arbuthnott [8] warns us that "attitudes and intentions are not the sole, or perhaps even the primary, influence on behavior. Thus, intervention programs will be more successful if behavioral factors in addition to attitudes are addressed" (p. 154). The most important behavioral factors and the most studied are the specificity of behavioral intentions, contextual barriers to the intended behavior, and perceived control over the behavior or its consequences.

In psychology, the most well-known theory on the problematic relationship between attitudes and behaviors is the theory of reasoned action [10]. According to Azjen, an individual's decision to engage in a specific behavior can be predicted by his or her intention to engage in that behavior [10]. In turn, the intention is determined by personal attitudes, subjective norms and perceived behavioral control. This theory has many practical and valuable applications. It has been widely used in health education campaigns, but much less in pro-environmental interventions. It is relevant to mention that the theory of planned

behavior is a development and improvement of the theory of reasoned action [11] and constitutes the baseline for planning interventions aimed at attitude and behavioral change.

To conclude, the goal of environmental education is to foster pro-environmental information or knowledge, attitudes, values, and behaviors. Each represents specific degrees of influence and requires specific methods of intervention. Although changes in knowledge or attitudes are important, we have no doubts that changes in behavior will eventually contribute to the improvement of the quality of our environment.

Games and apps have a greater potential in producing a deeper and more lasting change than other methods of environmental education, given their positive prospects for use in formal and informal educational settings, and their appealing playfulness, especially for the present young generation. For example, holding a conference on a pro-environmental theme in front of a young audience did not change behaviors and probably neither values nor attitudes but it possibly amplified the knowledge the young people possessed about the discussed environmental issue [12].

1.2. Games and Gamification as Environmental Education Tools: Serious Games and Gamified Apps

Games are a handy tool because of their accessibility and popularity. They also have a relatively long history as an alternative tool used in education. Regarding their use to bring individuals closer to environmental issues and raise awareness of environmental risks, it is worth mentioning one of the earliest studies testing the impact of gaming on this issue. Robinson and Ausubel [13] considered that games can help to structure and trigger behaviors that prevent the climate changes created by the carbon dioxide resulting from burning fossil fuels. For a time, however, game studies focused on the negative impact of games, especially on the impact on young players [14].

In recent years, researchers are gradually becoming more aware that traditional education programs face important challenges in adapting information processing styles to adolescents and young people. The reception of information by young people is optimal when it suits their interests and their style of information processing. If it is true that "digital natives" [15] focus on other aspects of communication compared to the previous generations, then there is a new communicative paradigm. Thus, the facilitation of human–computer interaction (such as video games and mobile apps) can be the most obvious expression of it.

The attempts to combine the use of video games and pro-environmentalism are relatively numerous [16]. The United Nations (through the United Nations Decade of Education for Sustainable Development or the United Nations Environment Program) has recommended that some of the most popular video games (Angry Birds 2, Golf Clash, and Subway Surfers) should include pro-environmental messages [3,17]. Today's young generation, unlike previous generations, has benefited from consistent pro-environmental education [18]. As such, young people do not necessarily lack information, yet they still have not developed pro-environmental attitudes and behaviors.

Finding ways to engage the population is essential: the current generations are the ones who will face more or less important environmental crises [19]. They must be prepared to face the consequences of climate change. By knowing the cause and having the right attitudes, current generations will be able to propose policies favorable to nature conservation. In particular, they can change their behavior to avoid adversely affecting the environment.

Thus, "serious games" can be a vital tool in environmental education because they retain their playfulness, but they are not just for entertainment: they have well-defined goals and their elements interconnect to achieve those goals [20]. They pursue educational goals, such as promoting health and physical well-being, but they are also used to promote sustainability and encourage pro-environmental behavior [21].

The game, be it video or material (for example, tabletop games), engages the players and makes them continue and succeed. When playing, the individuals deindividualize

themselves and take on an identity suggested by the game, one that is more attractive than the real one [22]. At the same time, players enter a state of flux, in which time loses its value and all that matters are the events and successes in the game [23].

In many cases, the game design and its gameplay are likely to stimulate players' creativity. Games remove inhibitions from our daily social participation, make us less responsible for our decisions and actions, create the impression of freedom, and thus stimulate our willingness to innovate [24].

Video games have other qualities that make them more efficient and more sustainable learning methods. They are fun, which generates the desire to continue the playful activity and contributes to the involvement of the players [25]. Another mechanism by which games engage and involve players is decision making [26]. By being asked to make decisions, players learn more about the topic in question, experimenting with alternative approaches and results. In addition, games allow players to develop empathy, taking on different roles and perspectives and making them project themselves into the future, thus foreshadowing the consequences of their actions [27]. In the field of nature protection and sustainability, this aspect of video games is particularly useful.

The term 'app' is the short version for 'application' and originally referred to any application designed for a specific purpose to be installed on any hardware. However, the swift development, accessibility, and usage of mobile devices (i.e., smartphones and tablets) and the appearance of multiple 'app stores' changed the common understanding of the word. In addition to serious games, pro-environmental apps, especially those developed for use on mobile devices, have gained popularity and have increasingly been used in the last decade. Most of the apps developed for environmental education are gamified in the sense that they include game elements, such as point earning, badges, and/or leaderboards [28]. Emerging in the early 2000s, gamification may be defined as the "use of game design elements within non-game contexts" [29] (p. 1) through "the process of making activities more game-like" [30] (p. 6), and it is seen as a promising path for engaging individuals towards the achievement of specific outcomes in a variety of fields [31]. Although most applications have been developed and used for experimentation for education and training, gamification is nowadays considered a real 'industry practice' with 'products' relevant to health, innovation, heritage, crowdsourcing, civic engagement, marketing, etc. [32]. As some researchers argue [31,32], not all contexts are appropriate for gamification, but formal and informal educational settings are certainly susceptible to gamified designs. Furthermore, gamification has some important strengths in supporting environmental education, such as allowing the users of games and apps to simulate complex scenarios that would be rather costly and challenging in real life-situations [33], and showing promising positive effects on pro-environmental behaviors or behavioral intentions [3].

The interest in the use of technology for pro-environmental purposes has increased in recent years, but the domain is still relatively new. A few systematic reviews targeted the research using computer games and apps as pro-environmental tools. However, they were concerned with specific outcomes, such as energy saving [3], or were less interested in the quantitative outcomes of the studies [6]. In the current systematic review, we aimed to analyze quantitative studies focused on the use of serious games and apps designed to increase the users' levels of pro-environmental information, attitudes and behaviors. By verifying these interventions, we aim to provide valuable information regarding the outcomes they targeted, the efficiency, and the limitations of the current approaches. Furthermore, the inclusion of apps in the present work contributes to the recent but rather slow advancements in understanding the state of the art in interdisciplinary research dealing with the use of technology for environmental formal and informal education, as well as mending some research gaps to be addressed in future studies.

1.3. Research Questions

Against the conceptual framework presented above, the present systematic review attempts to answer the following research questions:

- Are pro-environmental information or knowledge, attitudes, and behaviors addressed separately or comprehensively in serious games and apps?
- What are the most visible environmental concerns covered in serious games and apps and how are these introduced to users (independently *versus* integrated or interconnected)?
- What are the research designs as well as the results reported in the studies testing various effects of serious games and apps?

In contrast with other similar systematic reviews e.g., [3,6], the present work aimed to identify the deepness of interventions through serious games and apps (whether they intend to raise awareness through pro-environmental information, to develop pro-environmental attitudes, or to foster corresponding behaviors, sequentially or in various combinations), to get a clear overview of environmental concerns addressed and the potential to integrate them in future applications and subsequent interventions, as well as the most frequent research designs and reported effects.

2. Method

2.1. Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were used in this systematic literature review [34]. We searched the databases Scopus and Web of Science for the following search terms: (1) "game" OR "app" OR "gamification" AND "pro-environmental behavior"; (2) "game" OR "app" OR "gamification" AND "pro-environmental attitude"; and (3) "game" OR "app" OR "gamification" AND "pro-environmental education". For both databases, the search was made within the articles' abstract, title, and keywords. Additional sources were included based on studying the reference lists of the previous reviews and using Google Scholar. The search was finalized on 2 February 2022.

2.2. Data Collection

Following PRISMA recommendations for reducing the researchers' bias, after the retrieval of all articles based on the search terms used in the previously mentioned databases, two authors independently undertook the following steps: the screening of the titles and the abstracts against the criteria developed and agreed upon in a prior step, full-text screening to make decisions on inclusion and exclusion of articles and reports, and full-text analysis for data extraction. All disagreements between the two researchers were solved through consensus and were strictly based on the following inclusion criteria: (a) the studies were published in peer-reviewed sources, such as journals of conference proceedings; (b) the studies presented at least one measure evaluating the effectiveness of the game or gamified app, which included measurements reflecting the change or potential increase in pro-environmental information, attitudes, and behaviors after using the game or the gamified app (the studies that presented only the simple evaluation of the elements of the game or app, such as mechanics, graphics, interface, and others, or the intention to use the game or app, were not included in the review); (c) the studies used at least one quantitative measure (single-item or multiple-item instruments that assessed the participants' information, attitudes, and behaviors after playing the game or using the app, or actual measurements for the resources used by the participants, such as energy or water consumption, and qualitative studies, such as those that exclusively used interviews, were excluded); (d) the studies presented adequate information regarding the samples (number of participants for each measurement and distribution in experimental or control groups) and the instruments (number of items, proper description of the items and the response scale, and examples for the items used in each scale); and (e) the studies were published in English.

The initial search in the databases resulted in 227 sources, after the exclusion of duplicates. All identified papers and related reports were evaluated based on the inclusion

criteria and the research works that failed to meet them were excluded. A flowchart depicting this process is shown in Figure 1.

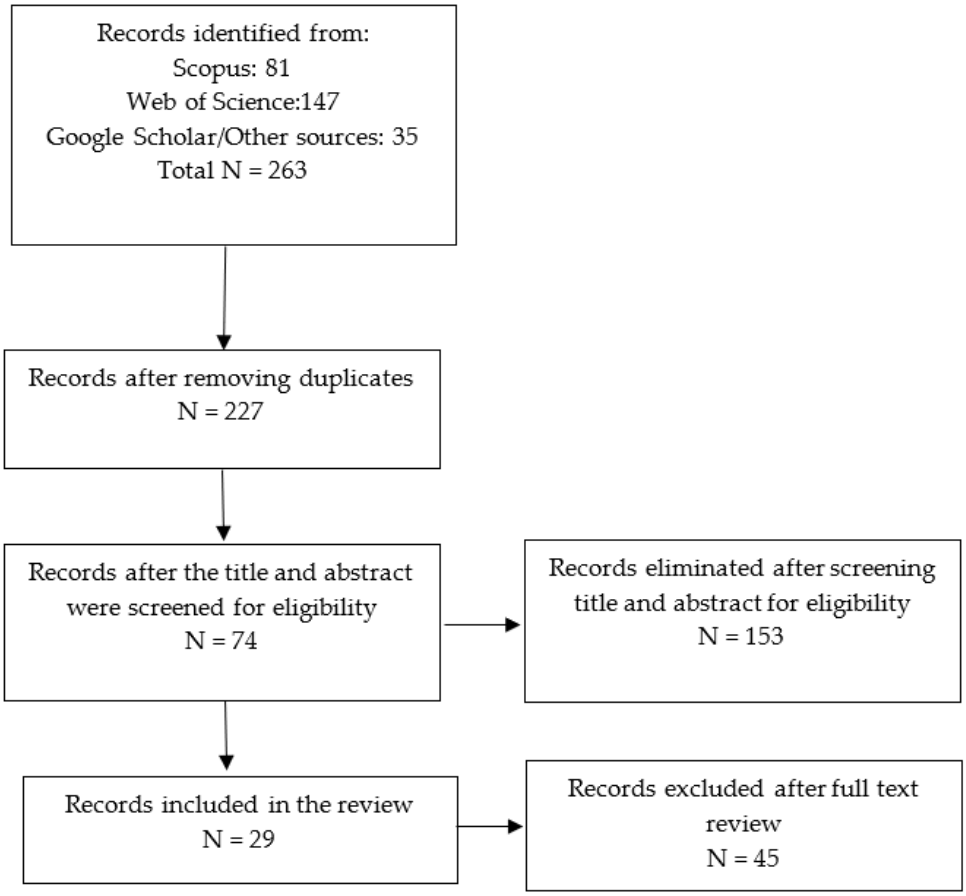

Figure 1. Flowchart detailing article search, article screening, data inclusions, and data exclusions.

2.3. Data Analysis

The final overall sample consisted of 29 papers (see Table 1). A two-layer analysis matrix was developed and employed for grouping the papers into categories and subcategories. The first layer was based on the theoretical background depicting the relation between pro-environmental information or knowledge, attitudes, and behavior [8,9] and thus addressed the deepness and specificity of engaging users of serious games and apps in pro-environmental change. We expected combinations of knowledge, attitudes, and behaviors to be targeted outcomes in the interventions based on serious games and apps. The second layer focused on the pro-environmental content illustrated in the serious games and apps tested in the selected research works. We based it on specific environmental issues summarized by Palmer concerning environmental education [35] (pp. 36–53), such as population growth, unsustainable agriculture and food consumption, deforestation, diminished biological diversity, "desertification and drought", unsustainable water consumption, deterioration of marine life, unsustainable use of energy, decline in air quality and deterioration of the ozone layer, poor waste management, unsustainable management of hazardous material, and "global security" issues determined by warfare and excessive military spending. A special note should be devoted to the second layer used in the data analysis: As environmental issues in terms of causes and effects are inherently interconnected, we expected some serious games and gamified apps to integrate more than one environmental concern. In addition to this theoretical framework, the unit of implementation or use of the serious games and apps, either individuals or groups (i.e.,

households, offices, and communities) was considered for deepening the analysis whenever appropriate.

Table 1. Information about the studies included in the review.

Authors	Name of Game/App	Type	Aim	Population	Results
Casals et al., 2020 [36]	EnergyCat: The House of Tomorrow	Mobile game	Improving household energy consumption	44 households	In the experimental group the energy consumption decreased by 3.46% and gas consumption decreased by 7.48%. These results are better than in the control group (where the consumption increased), but the difference was not significant.
Cellina et al., 2019 [37]	GoEco!	Mobile app with gamification elements	Increasing sustainable mobility (decreasing CO_2 emissions and average energy consumption per kilometer).	212 individuals in two urban areas	A randomized control trial with a one-year period was used. Significant decreases in CO_2 emissions and average energy consumption per kilometer were observed only for regularly traveled routes and only in the highly car-dependent areas. In the area where public transportation was highly available, the results were not significant.
Centieiro et al., 2011 [38]	Gaea	Multiplayer serious mobile game	Informing about and encouraging recycling behaviors	37 individuals	95% of the users considered that the game increased their awareness of recycling. 58% of the participants answered positively, 37% said probably and 5% answered negatively when asked if they were motivated by the game to start or to continue recycling.
Eder, 2016 [39]	IThrash	Serious mobile game	Practicing proper waster segregation	20 preschool students	After playing the game, the students correctly recognized 84% of the biodegradable items and 85% of the non-biodegradable items they were asked about.
Fijnheer et al., 2019 [40]	PowerSaver	Serious computer game	Improving household energy consumption	15 households	During the intervention, the total energy conservation in the experimental group was 20.9% (compared to 3.7% in the control group) and the electric energy conservation was 16.7% (in the control group the consumption grew). Both differences were significant. The difference in gas consumption was not significant, although the conservation was higher in the experimental group. After 21 days, all the differences became significant in favor of the experimental condition.
Fox et al., 2020 [41]		Serious computer game	Increasing pro-environmental behaviors and the support for pro-environmental policies	190 participants	The participants were divided into four conditions. Being psychologically closer to the environment leads to more pro-environmental behaviors and more support for policies. This link was mediated by risk perception. Being more contingent on environmental cleaning led to more pro-environmental behaviors and more support for policies. The link was mediated by self-efficacy.
Gabrielli and Maimone, 2013 [42]		Mobile app with gamification elements	Improving the adoption of more sustainable transportation methods	8 participants	After a four weeks pilot study (1 week of baseline measurement and 3 weeks for intervention), the use of sustainable transportation methods (carpooling, public transport, bike, walking etc.) grow by 14%. Four participants reported an increase in sustainable transportation use, while two of the reported a decrease.
Geelen et al., 2012 [43]	Energy Battles	Serious computer game	Improving household energy consumption	17 households	During the intervention decreased by 24% overall, with a maximum of 45%. One month after the intervention, most households reported higher levels of consumption and only two of them reported continuous drops.
Gustafsson et al., 2004 [44]	Power Explorer	Serious mobile game	Improving household energy consumption	15 participants in the experimental group and 20 households in the control group	10 weeks after the trial, the household energy consumption in the experimental group was 14% lower compared to the control group. However, due to the low sample, the difference was not significant. The participants in the experimental group also showed more positive attitudes towards energy saving.

Table 1. *Cont.*

Authors	Name of Game/App	Type	Aim	Population	Results
Hansmann et al., 2005 [45]	SIMULME	Online simulation game	Improving environmental knowledge, attitudes, and behaviors regarding food consumption	Study 1: 215 students; Study 2: 212 participants	Study 1: A significantly higher increase in pro-environmental attitudes was found in the experimental condition, compared to the control condition. The same trend was found in individual attitudes (preferring regional products, reduction of meat consumption, fair animal husbandry, the orientation towards the biological production of vegetables). Study 2: The purchasing behavior of the experimental group was significantly different compared to the control group. The former purchased more bio-labeled products and turned over exotic fruits less often. No differences were found regarding meat consumption.
Iria et al., 2020 [46]	GReSBAS	Mobile app with gamification elements	Improving energy efficiency in office building	24 employees working in an office building	Energy consumption in the office buildings was measured for six months. Using the app led to a drop of 20% in energy consumption. On weekdays, the energy consumption of the computers decreased by 15% during lunch breaks and by 26% during the night. The energy consumption of lights decreased by 6%. During weekends, the energy consumption of computers decreased by 34% and that of lights by 56%. Between 20–30% of the employees began to turn their computers at lunch and at night and 50% of them during the weekend.
Janakiraman, Watson, and Waston, 2021 [47]	EnerCities	Serious computer game	Informing about renewable and non-renewable energy sources	131 11th grade students	The game encouraged more pro-environmental attitudes in the experimental group (in both individual and collaborative players), compared to the control group.
Janakiraman, Watson et al., 2021 [48]	EnerCities	Serious computer game	Informing about renewable and non-renewable energy sources	94 undergraduate students	For the group who played EnerCities, the effect of affective, behavioral and social learning on environment-related behavioral intentions was stronger after one week, compared to the group who played a control game. After five weeks, the influence of social learning was still stronger for the experimental group.
Kawaguchi et al., 2018 [49]	Satoyama Management Game	Virtual world-simulation with gamification elements	Improving the understanding of forests' vegetation succession	15 BA and MA students	Over the three gaming sessions, the participants achieved more effective management strategies regarding vegetation succession. Their scores from the second and third attempts were significantly better compared to their first attempt.
Koroleva et al., 2019 [50]		Mobile app with gamification elements	Improving household energy consumption	100 households	Significant differences in energy saving compared to baseline were found between the intervention group (5.81) and the control group (1.33%).
Moore and Yang, 2019 [51]	Eco	Serious computer game	Teaching collaboration is maintaining an endangered ecosystem	Study 1:61 participants Study 2:293 participants	In the first study, playing the game did not lead to actual pro-environmental behavior (compared to the control group). Also, playing the game was not related to environmental intentions. In the second study, watching the trailer for the game did not lead to significantly higher environmental intentions (compared to the control group). Empathy and eco-guilt were not significant mediators of the proposed relationships in either study.
Mulcahy et al., 2020 [52]		Mobile app with gamification elements	Improving household energy consumption	326 participants in the experimental group	The energy bill savings over a period of four months for the group who used the app were significantly higher compared to the control group.
Neset et al., 2020 [53]	The Climate Adaptation game	Serious computer game	Informing about climate adaptation and increasing the understanding of its links to sustainable development goals	195 15 to 19 years old participants	Playing the game motivated 82% of the participants to learn more about climate adaptation. 79% of them considered they learn something new on the topic after playing the game.
Novak et al., 2018 [54]	SmartH20	Web app with gamification elements	Improving household water consumption	35 participants	Compared to baseline, the users reported an average reduction of 27.5% in water consumption, with 17 users reporting a drop of more than 30%.

Table 1. *Cont.*

Authors	Name of Game/App	Type	Aim	Population	Results
Oppong-Tawiah et al., 2020 [55]		Mobile app with gamification elements	Improving energy consumption in the office (consumed by computers and peripheral devices)	12 office stuff	After a three-step experiment (2 weeks for baseline measures, 2 weeks for intervention and two weeks for post-intervention measure), energy consumption was significantly lower during the intervention period compared to baseline ($r = -0.56$) and during the post-intervention period compared to baseline ($r = -0.37$). A non-significant difference between post-intervention and intervention was found.
Orland et al., 2014 [56]	Energy Chickens	Serious computer game	Improving energy efficiency in office buildings	57 participants	Energy consumption declined by 13% (23% during the non-work days and 7% during the workdays). For a group that played the game during the entire intervention, energy consumption declined significantly from baseline to intervention, but the trend was not kept during the follow-up. For the group that only viewed posters and other information about the game, energy consumption dropped during the late phases of the intervention, but it did not retain during the follow-up.
Ouariachi et al., 2018 [57]	2020Energy	Serious computer game	Improving attitudes about climate change and energy-related issues.	108 teenagers from Spain and the USA	The difference in attitude change between the experimental group and the control group was non-significant.
Rossano et al., 2018 [58]	Sea Adventure	Serious computer game	Informing about marine litter and endangered Mediterranean species	46 4th grade students	83% of the participants considered they acquired new knowledge. 88% of participants considered they will remember the information presented by the game.
Rossano et al., 2020 [59]	Sea Adventure	Serious computer game	Informing about marine litter and endangered Mediterranean species	50 4th grade students	Compared to the pre-test, the knowledge regarding the topic improved (the means for the wrong answers was 6.28 in the pre-test and 3.12 in the post-test). A retention test performed one year later showed a further decrease in the mean of wrong answers regarding the top, to 2.16.
Santos et al., 2013 [60]	eVision	Mobile app with gamification elements	Improving environmental awareness and attitudes; Motivating towards pro-environmental behaviors	20 participants	A month after playing the game, the participants reported that they felt alerted about the Earth's problems and that they became more aware of their environment-related decisions.
Sipone et al., 2021 [61]	ClassCraft	Serious computer game	Informing children about sustainable mobility	75 10 to 11 years old students	After playing the game, the participants showed an increased awareness of the means of sustainable mobility (bicycle lanes, car sharing, bike sharing, public transport etc.).
Su, 2018 [62]		Mobile app with gamification elements	Understand the impact of environmental migration	156 participants	After using the app during the environmental education program, the participants from the experimental group reported significantly higher levels of environmental awareness, environmental conceptual knowledge, environmental values and attitudes, environmental action skills environmental action experience and better overall learning outcomes compared to those from the control group.
Wang et al., 2021 [63]	PEAR	Augmented reality serious game	Promoting various sustainable behaviors (recycling, planting trees, switching lights etc.), and informing about sustainability issues	37 students	After playing the game, the participants in the experimental control reported higher levels of behavioral control regarding sustainable behaviors compared to those from the control group. They also showed improved knowledge regarding sustainability issues.
Wemyss et al., 2019 [64]	Social Power	Mobile app with gamification elements	Improving household energy consumption	42 households in the experimental groups and 40 households in the control group	A one-year follow-up measurement after the intervention showed that the decrease in energy consumption that was initially found was not maintained in the experimental group compared to the control group.

After the full-text screening for inclusion or exclusion of the papers, the data were re-analyzed using the matrix developed on conceptual grounds, and grouped into three

large categories: (1) papers centered on effects at the level of pro-environmental information, knowledge, and awareness, with strong educational emphases; (2) papers that mainly analyzed the effects of serious games and apps on pro-environmental attitudes, even though, in some cases, either pro-environmental knowledge or behaviors were also assessed; and (3) papers that mainly addressed specific pro-environmental behaviors. To answer the second research question, within each category, subcategories corresponding to general or specific environmental concerns or issues targeted by the game or the gamified app were identified and applied for further analysis, whenever the data allowed. The third research question was answered by analyzing research designs and results within categories and through explicit descriptions provided case by case.

3. Results

Most of the studies included in the present review focused mainly on pro-environmental behavior change (N = 14), followed by studies addressing pro-environmental information or knowledge (N = 9) and attitude development (N = 6).

The first category, based on the first layer proposed for the data analysis, includes studies that mainly addressed the effects of serious games and apps on participants' environment-related information or knowledge and awareness of environmental concerns (N = 9). One of these studies reported interventions based on a gamified app. The technology applications included in this category consider the general environmental concerns in an integrated manner, and also specific environmental issues (e.g., air pollution, population and migration issues, marine life, and sustainable mobility). As a consequence, two subcategories can be distinctively described: studies focusing on knowledge and awareness of general environmental challenges (N = 5), and studies concentrating on specific environmental concerns (N = 4). In terms of research designs, five of the studies relied on a survey methodology [38,49,53,58,60] with various types of questionnaires as data collection tools and reported post-usage figures, three studies used a pre-test and post-test design with descriptive questionnaires and reported results as corresponding percentages or averages and computed differences between averages [39,59,61], and only one study was quasi-experimentally designed (pre-test and post-test; experimental and control groups) with results based on inferential statistics [62]. Most of the studies reported usability evaluation primarily for serious games and gamified apps and included secondary study outcome data on gains in environmental information or knowledge among participants. With two notable exceptions [53,62], the reported samples are relatively small and participants' ages are varied (from 4 to 55 years old, depending on environmental content and the games' or apps' functionalities and complexity). Regardless of the research design and the sample, studies consistently suggest positive effects for pro-environmental information and/or awareness.

Four of the eight studies testing the effects of different serious games on participants' environment-related knowledge and awareness are built on general sustainability challenges and sustainable development, and therefore are included in the first subcategory. The Climate Adaptation Game [53] is a web-based computer game that tasks the player with taking care of the sustainability of a virtual city. The player must make decisions regarding the city's density, agriculture, industry, and hospitals and housing. When the various challenges are completed, the player accumulates points. The information derived from playing the game was tested in a sample of students. Most players reported that they learned something new about sustainability and were motivated to learn even more.

Gaea [38] is a serious game designed to improve recycling behaviors. The main task of the game is to recycle virtual objects spread around a virtual world. After recycling an object, the player receives some information about the object. The game can be played be in teams in a competitive manner. While the game targets a specific behavior, the implementation study did not take into account actual recycling behaviors but rather their attitudes and intentions towards the behaviors. A total of 95% of the participants reported

that the game made them more aware of recycling and most of them said that they would start or continue recycling.

Satoyama Management Game [49] is a game developed to teach the players about vegetation succession and forest management. The players have the task to manage a forest using various decisions with variable levels of sustainability. The players receive feedback based on their actions (the forest can survive or go extinct) and points as rewards. The game was tested using three gaming sessions. During them, players developed significantly more efficient means of managing the forest.

ClassCraft [65] is a serious computer game designed to teach students information about sustainability. It was developed based on the popular massively multiplayer online role-playing game "World of Warcraft". A study by Sipone and collaborators [61] showed that playing the game improved the participants' (children between 10 and 11 years old) knowledge about the transportation they can use to increase the levels of sustainable mobility.

One of the studies based on an app, namely eVision [60] also addressed general sustainability issues, with a mobile app that offers the user the task to find and clean environmental threats. Better performances in the app are rewarded with points that can be used to customize the main character of the game, a polar bear. Additionally, upon completing tasks, the players are rewarded with pro-environmental information. A month after playing the game, the adult participants considered themselves more aware of sustainability issues and had more information on how their decisions could influence the environment.

The remaining four studies focus on marine literacy, sustainable migration, and waste management, and are consequently included in the second subcategory. Thus, SeaAdventure is a serious computer game designed to teach children marine literacy. The players assume the role of four endangered Mediterranean species that swim through a marine environment full of waste. The characters must swim towards an endpoint while feeding on fish and avoiding waste. The players also receive information about the diet, lifestyle, and habitat of the animals they play as. The game was tested in two studies. In the pilot study, most players considered the acquired new knowledge about aquatic life [58]. In a second, pre-test and post-test study, the accumulation of knowledge after playing the game was significant [59]. Furthermore, knowledge further improved when measured one year later.

Su [62] designed a game used to inform players about sustainable migration. The task is to build a city and to balance different economic and environmental aspects regarding the buildings. The player must protect the environment while also keeping the population satisfied and happy. Compared to a control group, the users who played the game reported higher levels of pro-environmental knowledge, values, attitudes, and skills.

IThrash [39] is a game designed for preschool children to teach them how to select waste. The game was tested on a sample of 20 4–5-year-old children who had to recognize various biodegradable and non-biodegradable items after playing the game. Successful recognition was higher than 80% for both categories of items.

The second category comprises studies conducted only with game-based designs and a main focus on attitude development and change (N = 6), although some behavioral intentions are also measured in some of the cases. Due to serious games' particularities, five of these addressed several environmental concerns in an integrated or interconnected manner and are included in the first subcategory, and one is included in the second subcategory, according to our second layer of analysis. In contrast with the research approaches described for the first category of studies, all of the works centered on environmental attitude change and behavioral intentions were based on experimental designs, with variations from mixed method studies reporting embedded qualitative data collection into post-test quantitative studies [47,48], to quasi-experiments [51,57,63] and randomized experiments [41]. The measures applied for data collection were generally well-designed scales for environmental attitudes and behavioral intentions, many of them constructed based on the theory of

planned behavior, with validity and reliability convincingly reported. Although, several participants were dropped in some cases e.g., [41], reasonable samples were reported in all studies, and in one study, it is presented against the power analysis performed in advance [48].

As previously mentioned, the first subcategory includes five different studies, exploring the effects of serious games on participants' general environmental attitudes. An augmented reality game, PEAR [63], was designed to improve players' attitudes regarding various environmental concerns, such as the accumulation of waste, afforestation, and water contamination. The player must take care of a robot whose aim is to revitalize a post-apocalyptic Earth. The game also proposes real-world exploration and some mini-games targeting some specific concerns. To test the game, the author used an experimental group (who played the game) and a control group, both of which were composed of students. After playing the game, the participants from the experimental group had more information about sustainability-related issues and showed more positive attitudes towards pro-environmental behaviors.

Fox and colleagues [41] designed an experiment that used a computer game to manipulate the psychological distance to a polluted environment and the contingency in cleaning the environment. Players control a virtual kayak and navigate a polluted river. Based on the conditions, the river is geographically and temporally close or far. Additionally, the players either had an active role in cleaning the river, or the river became cleaner by itself. Being psychologically closer to the river led to higher risk perceptions, more support for pro-environmental policies, and more pro-environmental behaviors. Moreover, having more contingency led to being more self-efficient and pro-environmentally involved. Pro-environmental behaviors were only measured using the participants' self-reports.

Eco [66] is a computer game in which players must collaborate to save the world from an incoming meteorite. In an experiment designed by Moore and Yang [51], the game was used to increase the players' level of eco guilt. Although experiencing the game was related to eco guilt, playing the game or watching a trailer for it did not lead to higher levels of pro-environmental attitudes or more pro-environmental behaviors.

EnerCities [67] is a game designed to teach players about urban sustainability. The players must build a city and deploy various tactics to make it as sustainable as possible (by using renewable energy sources, protecting the greenery, balancing natural resources, etc.). The game was used in a study by Janakiraman and colleagues [47]. The participants were divided into three groups: some played the game individually, others played in teams, and some did not play the game (the control group). The participants who played the game, regardless of the method, developed higher levels of pro-environmental attitudes compared to the control group. In another study [48], the same team tested the game on a sample of undergraduate students and found that, for those who played the game, affective, behavioral, and social learning were more effective in predicting environment-related behaviors than for those who played a control game.

Only one game-based intervention was included in the second subcategory, as it targeted a specific environmental challenge, energy consumption. 2020Energy is a game that tasks players to act as consultants for the virtual characters and help them make more sustainable decisions regarding energy consumption. The players must balance the social, environmental and economic aspects of the situations they are involved in. The game was tested with both American and Spanish teenagers [57]. However, a pre-test and post-test analysis showed that the participants' attitudes did not significantly change after playing the game.

The third category consists of studies focusing mainly on pro-environmental behaviors (N = 14). In contrast with studies addressing information, knowledge and awareness of environmental challenges and alternative solutions, as well as pro-environmental attitudes, studies targeting behavioral change based on the use of serious games (N = 5) and gamified apps (N = 9) are clearly robust in covering specific environmental concerns: energy consumption, N = 10; water consumption, N = 1; food consumption, N = 1; and mobility,

N = 2. All studies intended for changing energy-saving behaviors or behavioral intentions were conducted based on quasi-experimental or intervention designs with pre-test and post-test measurements. In some studies a within-subjects design was preferred [46,55,56]. In others, experimental or treatment and control or reference groups were compared. In most cases (N = 6), households were involved in evaluating energy-saving data, with small samples and rather important drop-offs. Three reviewed studies focused on office environments, reporting energy savings collectively [46,55] and individually [56]. One study [52] targeted behavioral changes at the individual level in a large sample using two online surveys administered prior to and after the use of the gamified app, with app analytics and consumption energy savings as objective evidences of the effects. A study aiming at improving water consumption in households [54] and a study focusing on optimizing transport choices and habits [42] employed post-test designs with small samples but resulted in encouraging behavioral changes. Another study targeting food consumption [45] used a between-subjects experimental design with rather numerous experimental and control groups and reported positive changes in consumption patterns. One ambitious study using a mobility app [37] was based on a randomized controlled trial, but reported high attrition rates and no statistical evidence that the use of the app produced effects on mobility patterns, decreases in energy consumption and CO_2 emissions per kilometer, and changes in systematic mobility.

As emphasized above, according to our analysis matrix, only one subcategory may be arguably presented, with studies grouped based on the specific environmental issue addressed.

3.1. Energy Consumption

The reduction of energy consumption was targeted in both household settings as well as in office settings. EnergyCat [36] is a mobile game developed to train people to consume less electricity and gas in their households. In the game, the participants must build their ideal house, which is populated by a virtual family. The game aims to improve the energy efficiency of the virtual house and the behaviors of its inhabitants to accumulate more points and virtual money. With more energy-saving tactics used, the happier and more financially secure the characters become. The actual energy consumption of the user is also taken into account. Thus, it is expected that some energy-reduction tactics used in the game will spill over and develop into real life behaviors. A pilot experiment comparing the energy consumption at baseline and after the intervention for the experimental and the control groups showed that electricity and gas consumption dropped between time points for the intervention group and grew for the control group. However, given the small samples, these differences were not statistically significant.

Fijnheer and colleagues [40] compared the efficacy of a web-based computer game and a simple dashboard. PowerSaver is a game that combines role-playing and point-and-click elements where the player must implement a series of real-world energy-saving tactics (for example, washing clothes at a low temperature) to save a virtual house. The game uses missions, quizzes, completion, and rewards to motivate the player. A dashboard offering the same information as the game without the gamified elements was used as a control. During the implementation, the measurements showed a significant drop in general energy consumption and electrical energy consumption for the group that played the game compared to the one that used the dashboard. Gas consumption was lower in the experimental group but not significantly different. On a post-intervention measure, all the differences became significant, thus indicating a long-term effect of playing the game.

Energy Battles [43] is a platform that offers the participants tips about energy saving, measures real-time energy consumption, and provides the opportunity to win a competitive game. Players must save energy in their households to accumulate points that are transformed into building blocks used to build a virtual building. The household with the most savings and the player with the most impressive building win. To test the platform, the authors used a pre-test/post-test intervention study. Energy-saving levels before the

intervention (baseline), during the intervention, and after the intervention were compared. Most households saved energy during the intervention (compared to baseline), with the average savings being 24%. However, a month after the intervention, only two households continued to improve their energy-saving levels.

Power Explorer [44] is a game where the player assumes the role of a blob. The aim is to make the blob's environment more secure (by saving energy in the player's real house, which is connected to the game) and to win duels with other players by showing more knowledge about energy saving or by implementing some short-term energy saving tactics in real life (for example, shutting down a radiator). The game was tested on a group of 15 children that played the game for seven days. The energy savings from their households were compared with the ones from 20 other households (the control group). Subsequent measurements showed that the experimental group achieved 14% more energy saving than the control group. In addition, they showed more positive attitudes towards saving energy. However, their differences in actual savings were not significant.

Koroleva and colleagues [50] designed an app that helps people visualize the effects of their energy saving (in terms of money savings and environmental benefits), as well as compare themselves with other people on a leaderboard. The app also offers tips on how to save energy more efficiently. This intervention was tested on a sample of 100 households with an eight-month implementation period. During the implementation period and compared to baseline, the energy consumption decreased by 5.81% in the intervention group and 1.33% in the control group, a statistically significant difference.

Social Power [64] is an app that offers tips, information about current energy savings, and feedback based on the weekly savings. The app can be used cooperatively between households or completely individually (to see who saves more energy). The app was tested in two cities, with the participants engaged either in cooperation or in competition. Immediately after the intervention, both groups reported higher energy savings compared to the control group. However, this pattern was not retained after a year when the differences between groups were no longer significant.

Mulcahy and colleagues [52] present a mobile app that includes three games, each targeting a specific behavior that could lead to household energy savings (cool—using a fan instead of air conditioning; wash—washing laundry more efficiently, using full loads and cold water; switch—switching off lights and home appliances). Playing the games brings more points. Additionally, the developers considered that word-of-mouth would also be important in the success of the app. The results showed that the users who used the app in a casual or hardcore manner saved more on their energy bills compared to a control group after four months of using time.

We also found three papers describing energy-saving efforts at the office. Iria and colleagues [46] presented an app that offers information about real-time energy consumption with computers and the lights from the office, tips on how to save energy, leaderboards regarding individual and team results, challenges, and virtual soccer matches. Positive results were found during the implementation period, with a mean energy saving level of 20% and a constant pattern of decreased consumption during day and night on weekdays and during weekends.

Oppong-Tawiah and colleagues [55] developed a similar app that measured the level of energy consumption with computers and other peripheral devices. They also implemented a system where the users had to take care of a virtual garden. The state of the garden was in direct relationship with their level of energy consumption. The app was tested on 12 employees in a three-step experiment (with measurements at baseline, during the intervention, and two weeks after the intervention). Energy saving was significantly higher during the interventions and after the intervention in comparison with the baseline measurement. However, the comparison between the intervention and post-intervention measurement led to no significant differences.

Energy Chickens [56] is a virtual-pet game where the player must take care of some chickens. The health and well-being of the chickens are directly related to the real-time

energy savings of the user. When the user saves more energy compared to baseline, the animals become healthier and grow. Low energy savings lead to more unhealthy chickens. During the implementation period, which took place in an office setting, some participants played the game, while others only viewed posters of the game or were in contact with the active players. For both groups, energy consumption declined during the intervention. However, the decline was constant and faster for those who played the game. During the follow-up measure, both groups reported levels of energy consumption similar to those at baseline.

3.2. Water Consumption

Smart H2O [54] is a gamified app that offers real-time feedback on household water consumption, tips for saving water, and some competitive elements, such as leaderboards and rewards for the best saving performances. The app was tested in a small pilot study involving 35 participants. After a three-month implementation period, the average water consumption decreased by 27.5% compared to the baseline. The decrease was higher for those who, at baseline, consumed medium-high and high amounts of water compared to those who consumed low or medium-low amounts of water. In a sample of households where the app was not used, the decrease in water consumption was only 8%.

3.3. Food Consumption

SIMULME [45] is an online simulation game that was developed to create a more sustainable base for food consumption. The game offers data and information about the effects of choosing either mass-produced or bio food and tries to increase social responsibility by presenting the player as a potential role model. Buying behaviors were measured after playing the game. Compared to a control group, the participants who played the game purchased more organic-labeled products and turned over exotic fruits less often. However, no differences were found regarding meat, vegetables, fruits, fish, or seasonal products.

3.4. Mobility

GoEco [37] is a persuasive app that offers users various incentives to use sustainable means of mobility. The app helps the users find alternative routes for their travels, allows them to set goals, offers weekly reports, and introduces gamification elements, such as challenges and leaderboards. The app was tested in two Swiss regions. The results of a randomized controlled trial showed significant differences based on region and the routes taken by the users. In the areas where transportation is highly car-dependent, using the app led to significantly decreased CO_2 emissions and energy consumption when the routes were usually traveled by the user. However, no differences were found regarding less-traveled routes. Additionally, in the areas where public transportation was highly available, the app did not bring a significant difference.

A similar model was proposed by Gabrielli and Maimone [42]. Their app also helps users to set goals regarding their use of sustainable transportation means and offers the possibility of self-monitoring their behaviors, rewards, and leaderboards. A small-scale pilot study with eight participants using user-reported travel data compared the mobility behavior before using the app and during the app's use. The results showed a 14% increase in the use of sustainable transportation means. However, improved behaviors were observed in only four participants.

4. Discussion

This review showed that using serious computer games and gamified apps can be a viable solution for teaching sustainability. Various pro-environmental pieces of information and knowledge, behaviors, and attitudes were targeted by technology and its use proved to be advantageous. However, there are still noticeable shortcomings that should be addressed in future research.

The studies reviewed in this paper were published between 2004 and 2021. However, most of them appeared in the decade before writing this report. Thus, using technology became a more significant part of environmental policy and intervention in the passing years. While researchers were interested in using technology for environmental protection since the start of the millennium, the number of studies grew exponentially in the more recent period. This shows that researchers are trying to find new ways to implement change regarding pro-environmental knowledge, behaviors, and attitudes and, due to the increased accessibility and use of technology, this seems to be a reasonable path to accomplish their goals.

A few common outcomes were especially relevant. Regarding the first research question, in terms of deepness and specificity of interventions based on serious games or gamified apps, various approaches were identified. According to our analysis matrix, we found three deepness levels for the interventions proposed by the studies. Some targeted environmental information or knowledge and others were more interested in changing attitudes, while most studies approached behavioral change. Thus, a relatively high level of specificity was found. However, there were also examples of studies that created interventions for more than one level [38,41,51]. Still, these are rather rare.

Although pro-environmental attitudes are usually related and predict pro-environmental behaviors, this relationship is not consistent across all positive pro-environmental behaviors [68,69]. Thus, in order to fully comprehend the impact and efficacy of using such technology, further studies regarding actual behaviors should be implemented. Additionally, information and attitudes were measured through self-reported questionnaires, which makes objective improvements hard to quantify.

One may note that studies reporting the use of games and apps aiming to improve environment-related knowledge are designed for younger ages (preschoolers and secondary school students), while studies focusing on the effects of games on attitudes, with respect to games and mobile apps on pro-environmental behavior, involved young and mature adults as well as households and professional communities. Similarly, more studies reporting interventions based on apps were found for behavior-oriented interventions. Whether this second observation makes sense in terms of participants' age and life experience or is due to the infancy of mobile apps' development and usage remains an open question to be answered.

In terms of environmental content and regarding the second research question, we must differentiate between the studies targeting knowledge, attitudes, and behaviors. While in the first two categories we can find serious games and gamified apps targeting both general and specific issues (such as recycling, marine literacy, air pollution, forest vegetation success, energy consumption, or sustainable mobility), when the technology approached behavioral change, only specific issues were targeted. Among these, the most covered was energy efficiency, followed by mobility, while issues such as water or food consumption were present in one study each.

One important advantage of this review is that it includes studies implementing the use of technology at various levels. Some studies target individuals, while others target households or small working groups. On a grander level, most of the interventions could be expanded to include entire communities, especially those aiming to reduce energy and water consumption. Our analysis shows that the use of games and apps can be efficient at any level. However, similar shortcomings were found regardless of these levels. Most interventions led to a decrease in resource use in the short term, but few of them retained this change in the long term. This shows that, regardless of the unit of implementation (individual versus group), a constant engagement with the game or app is needed to deploy the change.

The research designs used for testing serious games' and apps' effects on targeted knowledge, attitudes, and/or behaviors, which were part of the focus in the third research question, were varied. At the level of knowledge formation, most studies use questionnaires, with one (post-test) or two (pre-post-test) data gathering points. While at this level only

one study used a quasi-experimental design, for the other two levels (attitude and behavior change), all studies used experimental designs.

Furthermore, regarding the third research question, playing serious games and using apps appears to be an efficient way to teach pro-environmental information and to increase pro-environmental attitudes. Most of the studies targeting such outcomes found significant improvements after using the technology [48,51,63]. Some of these improvements were retained in late follow-up measures [41,59]. Still, some studies found that pro-environmental attitudes were not impacted by using games or apps [51,57].

The results regarding the interventions aimed at changing specific behaviors also show a relatively high level of efficiency. The studies covered in the present review suggest that when household energy saving is concerned, using an app or a game designed to reduce energy consumption has important benefits. Energy saving increased during and immediately after the intervention, although the increase was not always significant [36,40]. However, long-term results were not consistent. While some studies showed that the participants benefited for months after the interventions, others showed that energy savings returned to the baseline levels a year after the participants stopped playing the game [43,52]. Similar results were found in studies that targeted office energy saving. On the short term, the interventions were efficient and led to significant drops in energy consumption on weekdays and during the weekends [40]. One study showed that even a secondary exposure to the game had some benefits [56]. However, long-term behavior was less impacted by the interventions. Follow-up measures showed that energy saving stagnated or declined after the participants stopped using the games or apps [55]. Past reviews observed similarly mixed results [3]. Although our review includes more recent studies, this issue remained and must be addressed by future interventions.

Other behaviors targeted by the interventions included water usage and food consumption. The results of these studies were also positive, showing a significant decrease in water consumption and an increase in more sustainable food choices [45,54]. However, both studies included short-term measures. Additionally, in the case of food choices, not all of the more environmentally-aware behaviors were improved by the intervention.

Sustainable mobility seems to be least impacted by computer games and apps. However, the lack of significant results can be a consequence of the small samples used in some of the studies included in the review [42]. The one study that included a larger sample found some positive results, although not for all in the targeted population. When there are few sustainable transportation alternatives, using an app such as GoEco can lead to a decrease in energy use and CO_2 emissions [37].

Previous theoretical frameworks proposed a series of barriers that determine that people limit their involvement in behaviors related to climate change mitigation. Among other barriers, Gifford included a series of cognitive limitations that impede intervention [70]. Humans are, sometimes, ignorant about what happens to the environment and have little, if any, information about what changes they can make regarding environmental protection. This can come from a lack of instruction, an unrealistic sense of optimism, a judgmental discounting (undervaluing future risks), or environmental numbness (not knowing how to interpret environmental changes and not paying attention to the changes that are distant to us). Moreover, from a social comparison standpoint, people tend to compare themselves with others and engage in behaviors similar to others. Adhering to a norm that does not prioritize pro-environmental behaviors thus becomes another important barrier. Our results show that using games and apps designed to foster pro-environmental information, attitudes, and behaviors may remove many of these barriers.

A large number of the games and apps included in this review offer information about climate change as well as solutions to mitigate it. Thus, the users become more informed and more aware of the risks, but also about the steps they can take to change the situation. The gamification elements help them engage in active behaviors so they can develop self-efficacy in managing issues that were previously regarded with skepticism [71,72]. In addition, many games engage the users in competitive gameplay and offer symbolic

rewards for those with the best pro-environmental performances. Thus, not only do they increase the sense of community but they also create a norm regarding the benefits of having pro-environmental behaviors.

One previous meta-analysis [73] also showed that, among the factors related to adopting climate-change-related behaviors, descriptive norms (whether others are involved in similar actions), self-efficacy, and outcome efficacy presented the strongest links. Knowledge was also related to the outcome but the association was weaker. Using the findings of this paper can act as a very useful way to reinforce all of these mechanisms. In conclusion, using games and apps for engaging in pro-environmental behavior can remove the barriers that prevented the users from previously participating in such behaviors and can activate the psychological mechanisms that are related to stronger involvement in these actions.

5. Limitations of the Current Approaches

Although most of the interventions included in the analysis lead to some improvement, some general limitations of the current approaches should be noted. Gamification was a mechanism included in most of the games and apps. However, it was implemented differently from study to study. Some used leaderboards and others proposed competitive gameplay while others included various challenges for the player. Additionally, the interventions used different psychological mechanisms to achieve change. Previous analyses showed that the implementation of different components of the games can lead to different levels of effectiveness [16,74]. The implementation of a common methodology for all the interventions is needed, but given that there is still a consistent list of unknowns about why games work in this domain and that some crucial elements of game development (such as search optimization and discoverability) continue to be underutilized, this task could be quite difficult [2,75]. Future research should use a meta-analytic approach and differentiate between the various methodologies applied in the studies. If the study presents a game or an app as an intervention method, the various ways the psychological means for change are deployed could be used as moderators in such a study.

A second limitation is the use of small samples to test the technology. Most studies used under 100 participants to test their interventions. Moreover, these samples were divided into two or more groups, which further limited the number of participants for each group. For some studies, the lack of significant results can be explained by the small number of participants. On the contrary, in small-sample studies, significant results can also be a consequence of low samples, especially since the statistical power of the study was not usually reported. Consequently, larger samples should be used in order to achieve sufficient statistical power. A more detailed comparison between the studies would be approachable with a meta-analysis. Studies could be evaluated based on their statistical power. Moreover, a meta-analysis can compute an overall effect for all interventions while offering different weights for each study based on their sample, which would partially solve this problem.

Attrition was another significant problem present in some studies [37,40,63,64]. The studies that used long interventions and follow-up measures after the intervention were particularly affected by this issue. Thus, some of the non-significant long-time effects could also be a consequence of the low number of participants that remained in the studies. One particular reason for the low attrition could be offered by Boomsma and colleagues [1]. They found that some individuals used time pressures, negative perceptions of gaming, and limited confidence in using computers or tablets as reasons for not engaging with sustainability-supporting technology. Although this motivation could affect both short-term and long-term measurements, it is more probable that it would lead to more boredom and frustration for those who would use such technology for long periods.

A final limitation was also underlined by Hallinger and colleagues [6]. Most studies were developed in Western Europe. Contrary to previous results, few studies were conducted in the United States. Further cross-cultural diversity is needed to assess the actual efficiency of the games and apps. In addition, given the cultural differences between the

WEIRD (Western, educated, industrialized, rich, and democratic) countries and the rest of the world, it is possible that such games would not be suitable to use with the non-WEIRD population.

6. Conclusions

While taking into account these limitations, the use of serious computer games and mobile apps to develop pro-environmental information, attitudes, and behaviors seems to be beneficial. A variety of outcomes were targeted, and the intervention brought some significant improvements, although most were short-term. Continuous use of the technology seems to be necessary to expand its benefits into the long term. Researchers should also concentrate on developing a common methodology to develop, implement, and assess the interventions. Still, this domain study is relatively young, and the results are promising enough to encourage further efforts to develop sustainable information, attitudes, and behaviors through the use of computer games and apps.

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References

1. Boomsma, C.; Hafner, R.; Pahl, S.; Jones, R.; Fuertes, A. Should We Play Games Where Energy Is Concerned? Perceptions of Serious Gaming as a Technology to Motivate Energy Behaviour Change among Social Housing Residents. *Sustainability* **2018**, *10*, 1729. [CrossRef]
2. Douglas, B.D.; Brauer, M. Gamification to Prevent Climate Change: A Review of Games and Apps for Sustainability. *Curr. Opin. Psychol.* **2021**, *42*, 89–94. [CrossRef] [PubMed]
3. Morganti, L.; Pallavicini, F.; Cadel, E.; Candelieri, A.; Archetti, F.; Mantovani, F. Gaming for Earth: Serious Games and Gamification to Engage Consumers in pro-Environmental Behaviours for Energy Efficiency. *Energy Res. Soc. Sci.* **2017**, *29*, 95–102. [CrossRef]
4. Ro, M.; Brauer, M.; Kuntz, K.; Shukla, R.; Bensch, I. Making Cool Choices for Sustainability: Testing the Effectiveness of a Game-Based Approach to Promoting pro-Environmental Behaviors. *J. Environ. Psychol.* **2017**, *53*, 20–30. [CrossRef]
5. Torres-Toukoumidis, A.; León, D.V.; De-Santis, A.; López-López, P.C. Gamification in Ecology-Oriented Mobile Applications—Typologies and Purposes. *Societies* **2022**, *12*, 42. [CrossRef]
6. Hallinger, P.; Wang, R.; Chatpinyakoop, C.; Nguyen, V.-T.; Nguyen, U.-P. A Bibliometric Review of Research on Simulations and Serious Games Used in Educating for Sustainability, 1997–2019. *J. Clean. Prod.* **2020**, *256*, 120358. [CrossRef]
7. Stapp, W.B. The Concept of Environmental Education. *Environ. Educ.* **1969**, *1*, 30–31. [CrossRef]
8. Arbuthnott, K.D. Education for Sustainable Development beyond Attitude Change. *Int. J. Sustain. High. Educ.* **2009**, *10*, 152–163. [CrossRef]
9. Krajhanzl, J. Environmental and Pro-Environmental Behavior. In *School and Health 21, Health Education: International Experiences*; Řehulka, E., Ed.; Masaryk University Press: Brno, Czech Republic, 2010; pp. 251–274.
10. Ajzen, I. From Intentions to Actions: A Theory of Planned Behavior. In *Action Control*; Kuhl, J., Beckmann, J., Eds.; Springer: Berlin/Heidelberg, Germany, 1985; pp. 11–39.
11. Ajzen, I.; Fishbein, M. *Understanding Attitudes and Predicting Social Behavior*; Pearson: Upper Saddle River, NJ, USA, 1980.
12. Leeming, F.C.; Dwyer, W.O.; Porter, B.E.; Cobern, M.K. Outcome Research in Environmental Education: A Critical Review. *J. Environ. Educ.* **1993**, *24*, 8–21. [CrossRef]
13. Robinson, J.; Ausubel, J.H. A Game Framework for Scenario Generation for the Co2 Issue. *Simul. Games* **1983**, *14*, 317–344. [CrossRef]

14. Groves, C.L.; Anderson, C.A. Negative Effects of Video Game Play. In *Handbook of Digital Games and Entertainment Technologies*; Springer: Singapore, 2017; pp. 1297–1322.
15. Prensky, M. Digital Natives, Digital Immigrants Part 1. *Horizon* **2001**, *9*, 1–6. [CrossRef]
16. Ouariachi, T.; Li, C.-Y.; Elving, W.J.L. Gamification Approaches for Education and Engagement on Pro-Environmental Behaviors: Searching for Best Practices. *Sustainability* **2020**, *12*, 4565. [CrossRef]
17. Cars, M.; West, E.E. Education for Sustainable Society: Attainments and Good Practices in Sweden during the United Nations Decade for Education for Sustainable Development (UNDESD). *Environ. Dev. Sustain.* **2015**, *17*, 1–21. [CrossRef]
18. Wiernik, B.M.; Ones, D.S.; Dilchert, D.S. Age and Environmental Sustainability: A Meta-Analysis. *J. Manag. Psychol.* **2013**, *28*, 826–856. [CrossRef]
19. Lubchenco, J. Entering the Century of the Environment: A New Social Contract for Science. *Science* **1998**, *279*, 491–497. [CrossRef]
20. Anastasiadis, T.; Lampropoulos, G.; Siakas, K. Digital Game-Based Learning and Serious Games in Education. *Int. J. Adv. Sci. Res. Eng.* **2018**, *4*, 139–144. [CrossRef]
21. Stanitsas, M.; Kirytopoulos, K.; Vareilles, E. Facilitating Sustainability Transition through Serious Games: A Systematic Literature Review. *J. Clean. Prod.* **2019**, *208*, 924–936. [CrossRef]
22. Chen, V.H.H.; Wu, Y. Group Identification as a Mediator of the Effect of Players' Anonymity on Cheating in Online Games. *Behav. Inf. Technol.* **2015**, *34*, 658–667. [CrossRef]
23. Hamari, J.; Shernoff, D.J.; Rowe, E.; Coller, B.; Asbell-Clarke, J.; Edwards, T. Challenging Games Help Students Learn: An Empirical Study on Engagement, Flow and Immersion in Game-Based Learning. *Comput. Hum. Behav.* **2016**, *54*, 170–179. [CrossRef]
24. Moffat, D.C.; Crombie, W.; Shabalina, O. Some Video Games Can Increase the Player's Creativity. *Int. J. Game-Based Learn.* **2017**, *7*, 35–46. [CrossRef]
25. Djaouti, D.; Alvarez, J.; Jessel, J.-P.; Rampnoux, O. Origins of Serious Games. In *Serious Games and Edutainment Applications*; Springer: London, UK, 2011; pp. 25–43.
26. Fabricatore, C.; López, X. Sustainability Learning through Gaming: An Exploratory Study. *Electron. J. e-Learn.* **2012**, *10*, 209–222.
27. Bachen, C.M.; Hernández-Ramos, P.; Raphael, C.; Waldron, A. How Do Presence, Flow, and Character Identification Affect Players' Empathy and Interest in Learning from a Serious Computer Game? *Comput. Hum. Behav.* **2016**, *64*, 77–87. [CrossRef]
28. Leitão, R.; Maguire, M.; Turner, S.; Arenas, F.; Guimarães, L. Ocean Literacy Gamified: A Systematic Evaluation of the Effect of Game Elements on Students' Learning Experience. *Environ. Educ. Res.* **2022**, *28*, 276–294. [CrossRef]
29. Deterding, S.; Dixon, D.; Khaled, R.; Nacke, L. From Game Design Elements to Gamefulness: Defining "Gamification". In Proceedings of the 15th International Academic MindTrek Conference on Envisioning Future Media Environments—MindTrek '11, Tampere, Finland, 28–30 September 2011; ACM Press: New York, NY, USA, 2011.
30. Werbach, K. (Re) Defining Gamification: A Process Approach. In *Persuasive Technology*; Springer International Publishing: Cham, Switzerland, 2014; pp. 266–272.
31. Sailer, M.; Hense, J.U.; Mayr, S.K.; Mandl, H. How Gamification Motivates: An Experimental Study of the Effects of Specific Game Design Elements on Psychological Need Satisfaction. *Comput. Human Behav.* **2017**, *69*, 371–380. [CrossRef]
32. Nacke, L.E.; Deterding, S. The Maturing of Gamification Research. *Comput. Hum. Behav.* **2017**, *71*, 450–454. [CrossRef]
33. Madani, K.; Pierce, T.W.; Mirchi, A. Serious Games on Environmental Management. *Sustain. Cities Soc.* **2017**, *29*, 1–11. [CrossRef]
34. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann. Intern. Med.* **2009**, *151*, 264–269. [CrossRef]
35. Palmer, J. *Environmental Education in the 21st Century: Theory, Practice, Progress and Promise*; Routledge: London, UK, 2002.
36. Casals, M.; Gangolells, M.; Macarulla, M.; Forcada, N.; Fuertes, A.; Jones, R.V. Assessing the Effectiveness of Gamification in Reducing Domestic Energy Consumption: Lessons Learned from the EnerGAware Project. *Energy Build.* **2020**, *210*, 109753. [CrossRef]
37. Cellina, F.; Bucher, D.; Mangili, F.; Veiga Simão, J.; Rudel, R.; Raubal, M. A Large Scale, App-Based Behaviour Change Experiment Persuading Sustainable Mobility Patterns: Methods, Results and Lessons Learnt. *Sustainability* **2019**, *11*, 2674. [CrossRef]
38. Centieiro, P.; Romão, T.; Dias, A.E. A Location-Based Multiplayer Mobile Game to Encourage pro-Environmental Behaviours. In Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology—ACE '11, Lisbon, Portugal, 8–11 November 2011; ACM Press: New York, NY, USA, 2011.
39. Eder, M.S. ITrash: Proper Waste Segregation Mobile Game. *Indian J. Sci. Technol.* **2016**, *9*, 1–8. [CrossRef]
40. Fijnheer, J.D.L.; Van Oostendorp, H.; Veltkamp, R. Household Energy Conservation Intervention: A Game versus Dashboard Comparison. *Int. J. Serious Games* **2019**, *6*, 23–36. [CrossRef]
41. Fox, J.; McKnight, J.; Sun, Y.; Maung, D.; Crawfis, R. Using a Serious Game to Communicate Risk and Minimize Psychological Distance Regarding Environmental Pollution. *Telemat. Inform.* **2020**, *46*, 101320. [CrossRef]
42. Gabrielli, S.; Maimone, R. Digital Interventions for Sustainable Urban Mobility: A Pilot Study. In Proceedings of the 2013 ACM Conference on Pervasive and Ubiquitous Computing Adjunct Publication, Zurich, Switzerland, 8–12 September 2013; ACM: New York, NY, USA, 2013.
43. Geelen, D.; Keyson, D.; Boess, S.; Brezet, H. Exploring the Use of a Game to Stimulate Energy Saving in Households. *J. Des. Res.* **2012**, *10*, 102. [CrossRef]

44. Gustafsson, A.; Bång, M.; Svahn, M. Power Explorer: A Casual Game Style for Encouraging Long Term Behavior Change among Teenagers. In Proceedings of the International Conference on Advances in Computer Enterntainment Technology—ACE '09, Athens, Greece, 29–31 October 2009; ACM Press: New York, NY, USA, 2009.
45. Hansmann, R.; Scholz, R.W.; Francke, C.-J.A.C.; Weymann, M. Enhancing Environmental Awareness: Ecological and Economic Effects of Food Consumption. *Simul. Gaming* **2005**, *36*, 364–382. [CrossRef]
46. Iria, J.; Fonseca, N.; Cassola, F.; Barbosa, A.; Soares, F.; Coelho, A.; Ozdemir, A. A Gamification Platform to Foster Energy Efficiency in Office Buildings. *Energy Build.* **2020**, *222*, 110101. [CrossRef]
47. Janakiraman, S.; Watson, S.L.; Watson, W.R. Exploring the Effectiveness of Digital Games in Producing Pro-Environmental Behaviors When Played Collaboratively and Individually: A Mixed Methods Study in India. *TechTrends* **2021**, *65*, 331–347. [CrossRef]
48. Janakiraman, S.; Watson, S.L.; Watson, W.R.; Newby, T. Effectiveness of Digital Games in Producing Environmentally Friendly Attitudes and Behaviors: A Mixed Methods Study. *Comput. Educ.* **2021**, *160*, 104043. [CrossRef]
49. Kawaguchi, S.; Mizoguchi, H.; Egusa, R.; Takeda, Y.; Yamaguchi, E.; Inagaki, S.; Kusunoki, F.; Funaoi, H.; Sugimoto, M. A Forestry Management Game as a Learning Support System for Increased Understanding of Vegetation Succession—Effective Environmental Education towards a Sustainable Society. In Proceedings of the 10th International Conference on Computer Supported Education, Madeira, Portugal, 15–17 March 2018; Science and Technology Publications: Setúbal, Portugal, 2018.
50. Koroleva, K.; Melenhorst, M.; Novak, J.; Herrera Gonzalez, S.L.; Fraternali, P.; Rizzoli, A.E. Designing an Integrated Socio-Technical Behaviour Change System for Energy Saving. *Energy Inform.* **2019**, *2*, 30. [CrossRef]
51. Moore, M.M.; Yang, J.Z. Using Eco-Guilt to Motivate Environmental Behavior Change. *Environ. Commun.* **2020**, *14*, 522–536. [CrossRef]
52. Mulcahy, R.; Russell-Bennett, R.; Iacobucci, D. Designing Gamified Apps for Sustainable Consumption: A Field Study. *J. Bus. Res.* **2018**, *106*, 377–387. [CrossRef]
53. Neset, T.-S.; Andersson, L.; Uhrqvist, O.; Navarra, C. Serious Gaming for Climate Adaptation—Assessing the Potential and Challenges of a Digital Serious Game for Urban Climate Adaptation. *Sustainability* **2020**, *12*, 1789. [CrossRef]
54. Novak, J.; Melenhorst, M.; Micheel, I.; Pasini, C.; Fraternali, P.; Rizzoli, A.E. Integrating Behavioural Change and Gamified Incentive Modelling for Stimulating Water Saving. *Environ. Model. Softw.* **2018**, *102*, 120–137. [CrossRef]
55. Oppong-Tawiah, D.; Webster, J.; Staples, S.; Cameron, A.-F.; Ortiz de Guinea, A.; Hung, T.Y. Developing a Gamified Mobile Application to Encourage Sustainable Energy Use in the Office. *J. Bus. Res.* **2018**, *106*, 388–405. [CrossRef]
56. Orland, B.; Ram, N.; Lang, D.; Houser, K.; Kling, N.; Coccia, M. Saving Energy in an Office Environment: A Serious Game Intervention. *Energy Build.* **2014**, *74*, 43–52. [CrossRef]
57. Ouariachi, T.; Gutiérrez-Pérez, J.; Olvera-Lobo, M.-D. Can Serious Games Help to Mitigate Climate Change? Exploring Their Influence on Spanish and American Teenagers'. *Psyecology* **2018**, *9*, 365–395. [CrossRef]
58. Rossano, V.; Roselli, T.; Calvano, G. A Serious Game to Promote Environmental Attitude. In *Smart Education and e-Learning 2017*; Springer International Publishing: Cham, Switzerland, 2018; pp. 48–55.
59. Rossano, V.; Calvano, G. Promoting Sustainable Behavior Using Serious Games: SeAdventure for Ocean Literacy. *IEEE Access* **2020**, *8*, 196931–196939. [CrossRef]
60. Santos, B.; Romão, T.; Dias, A.E.; Centieiro, P. EVision: A Mobile Game to Improve Environmental Awareness. In *Lecture Notes in Computer Science*; Springer International Publishing: Cham, Switzerland, 2013; pp. 380–391.
61. Sipone, S.; Abella-García, V.; Rojo, M.; dell'Olio, L. Using ClassCraft to Improve Primary School Students' Knowledge and Interest in Sustainable Mobility. *Sustainability* **2021**, *13*, 9939. [CrossRef]
62. Su, C.-H. Exploring Sustainability Environment Educational Design and Learning Effect Evaluation through Migration Theory: An Example of Environment Educational Serious Games. *Sustainability* **2018**, *10*, 3363. [CrossRef]
63. Wang, K.; Tekler, Z.D.; Cheah, L.; Herremans, D.; Blessing, L. Evaluating the Effectiveness of an Augmented Reality Game Promoting Environmental Action. *Sustainability* **2021**, *13*, 13912. [CrossRef]
64. Wemyss, D.; Cellina, F.; Lobsiger-Kägi, E.; de Luca, V.; Castri, R. Does It Last? Long-Term Impacts of an App-Based Behavior Change Intervention on Household Electricity Savings in Switzerland. *Energy Res. Soc. Sci.* **2019**, *47*, 16–27. [CrossRef]
65. Sanchez, E.; Young, S.; Jouneau-Sion, C. Classcraft: From Gamification to Ludicization of Classroom Management. *Educ. Inf. Technol.* **2017**, *22*, 497–513. [CrossRef]
66. Strange Loop Games. *Eco, Version Beta*; Strange Loop Games: Seattle, WA, USA, 2015.
67. Knol, E.; De Vries, P.W. EnerCities, a Serious Game to Stimulate Sustainability and Energy Conservation: Preliminary Results. *Elearning Pap.* **2011**, *25*, 1–10.
68. Árnadóttir, Á.; Czepkiewicz, M.; Heinonen, J. The Geographical Distribution and Correlates of Pro-Environmental Attitudes and Behaviors in an Urban Region. *Energies* **2019**, *12*, 1540. [CrossRef]
69. Tian, H.; Zhang, J.; Li, J. The Relationship between Pro-Environmental Attitude and Employee Green Behavior: The Role of Motivational States and Green Work Climate Perceptions. *Environ. Sci. Pollut. Res. Int.* **2020**, *27*, 7341–7352. [CrossRef]
70. Gifford, R. The Dragons of Inaction: Psychological Barriers That Limit Climate Change Mitigation and Adaptation. *Am. Psychol.* **2011**, *66*, 290–302. [CrossRef]
71. Banfield, J.; Wilkerson, B. Increasing Student Intrinsic Motivation and Self-Efficacy through Gamification Pedagogy. *Contemp. Issues Educ. Res.* **2014**, *7*, 291–298. [CrossRef]

72. Polo-Peña, A.I.; Frías-Jamilena, D.M.; Fernández-Ruano, M.L. Influence of Gamification on Perceived Self-Efficacy: Gender and Age Moderator Effect. *Int. J. Sports Mark. Spons.* **2021**, *22*, 453–476. [CrossRef]
73. van Valkengoed, A.M.; Steg, L. Meta-Analyses of Factors Motivating Climate Change Adaptation Behaviour. *Nat. Clim. Chang.* **2019**, *9*, 158–163. [CrossRef]
74. Wood, G.; van der Horst, D.; Day, R.; Bakaoukas, A.G.; Petridis, P.; Liu, S.; Jalil, L.; Gaterell, M.; Smithson, E.; Barnham, J.; et al. Serious Games for Energy Social Science Research. *Technol. Anal. Strat. Manag.* **2014**, *26*, 1212–1227. [CrossRef]
75. Beck, A.L.; Chitalia, S.; Rai, V. Not so Gameful: A Critical Review of Gamification in Mobile Energy Applications. *Energy Res. Soc. Sci.* **2019**, *51*, 32–39. [CrossRef]